

Hydrogeology for Underground Injection Control in Michigan:

Part 1



**Department of Geology
Western Michigan University
Kalamazoo, Michigan**

**U.S. Environmental Protection Agency
Underground Injection Control Program**

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Acknowledgements

ADMINISTRATIVE STAFF

DENNIS L. CURRAN
Project Coordinator

LINDA J. MILLER
Cartographer

DONALD N. LESKE
Regional Coordinator

PROJECT DIRECTORS

RICHARD N. PASSERO
Ph.D., Professor of Geology

W. Thomas Straw
Ph.D., Professor of Geology

Lloyd J. Schmaltz
Chairman, Department of Geology

Department of Geology, Western Michigan University

RESEARCH STAFF

CYNTHIA BATHRICK
PAUL CIARAMITARO
PATRICIA DALIAN
DOUGLAS DANIELS
DARCEY DAVENPORT
JEFFREY DEYOUNG
GEORGE DUBA
SHARON EAST
JAMES FARNSWORTH
LINDA FENNER

WILLIAM GIERKE
PAUL GOODREAULT
DAVID HALL
EVELYN HALL
THOMAS HANNA
ROBERT HORNTVEDT
JON HERMANN
WILLIAM JOHNSTON
PHILLIP KEAVEY

CRYSTAL KEMTER
STEVEN KIMM
KEVIN KINCARE
MICHAEL KLEIN
BARBARA LEONARD
THOMAS LUBY
HALLY MAHAN
JAMES McLAUGHLIN
DEANNA PALLADINO
DONALD PENNEMAN

JEFFREY PFOST
NICK POGONCHEFF
KIFF SAMUELSON
JEFFREY SPRUIT
GARY STEFANIAK
JOSEPH VANDERMEULEN
LISA VARGA
KATHERINE WILSON
MICHAEL WIREMAN

CARTOGRAPHIC STAFF

LINDA J. MILLER
Chief Cartographer

SARAH CUNNINGHAM
DAVID MOORE
NORMAN AMES
PATRICK HUDSON

CAROL BUCHANAN
KENNETH BATTS
ANDREW DAVIS
MARK LUTZ

ARLENE D. SHUB
CHRISTOPHER H. JANSEN
ANN CASTEL
JOAN HENDRICKSEN

MAPPING CONSULTANT

THOMAS W. HODLER
Ph.D., Assistant Professor of Geography
Department of Geography
Western Michigan University

CLERICAL PERSONNEL

KARN KIK

JANET NIEWOONDER

LINDA WYRICK

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I. INTRODUCTION

A. Foreword

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FOREWORD

The Hydrogeology for Underground Injection Control in Michigan and its companion volume, the Hydrogeologic Atlas of Michigan, are a unique compendium of text, maps, cross sections and tables synthesizing current and classical information on the hydrology and geology of the State of Michigan. Heretofore, no single reference has offered access to the wealth of hydrogeologic data evolved by researchers and authors throughout the years. The report represents two years of extensive investigation to identify, evaluate, organize and compile relevant and reputable contributions to the hydrogeologic data base of Michigan. Although the primary focus is on the hydrogeology of the State, the report also summarizes the past underground injection operations in Michigan. The Atlas contains many geologic structure, isopachous, lithofacies and other maps which lend a foundation for interpreting and understanding the hydrogeology of Michigan. As such, the report will be eminently useful, if not essential, to a broad spectrum of professionals in a variety of fields ranging from engineering firms and oil companies to planning councils and governmental agencies.

PLANNING AND FUNDING

In 1974, P.L. 93-523 (the Safe Drinking Water Act) was signed into law. Section 1421, Part C of the Act, dealt with the protection of the underground sources of drinking water and the underground injection of wastes. Primary responsibility for the Underground Injection Control Program was given to the United States Environmental Protection Agency (E.P.A.). In 1978, E.P.A. began the administration of the program in Michigan and in 1979, the Department of Geology of Western Michigan University was awarded the first of two grants totaling \$650,000 to provide geologic data prerequisite to issuing permits for underground injection wells. After organizational meetings with personnel from Region V (E.P.A.) and the University, a team of administrators, consultants and research assistants was assembled and exploratory searches were initiated. What was to become a very fluid, but persistent, effort was begun.

SCOPE

The effort was essentially a review and compilation of existing data, mostly published information, but also unpublished information such as that stored in the files of County, State and Federal agencies. University libraries were visited by graduate and undergraduate assistants and requested to provide theses and dissertations related to Michigan geology. Project coordinators and assistants visited county, city and federal agencies to obtain information on ground-water resources and water quality. Maps and studies were requested from geologists most

knowledgeable about the hydrology and geology of the State including those engaged in federally-funded and industry-sponsored research. WATSTORE was made operational and its content validated. This report and a companion volume, the Hydrogeologic Atlas of Michigan, are the culmination of these efforts.

STAFFING

The project was accomplished by a team of staff and students from the Department of Geology of Western Michigan University, under the direction of Mr. Dennis L. Curran, and Mr. Donald N. Leske (project coordinators), Dr. Richard N. Passero, Dr. W. Thomas Straw (project co-directors), and Dr. Lloyd J. Schmaltz (chairman, Department of Geology). The Atlas was prepared under the cartographic direction of Ms. Linda J. Miller and in consultation with Dr. Thomas Hodler, Department of Geography. Most of the detailed work was done by 75 graduate and undergraduate students from the Departments of Geology and Geography.

LIMITATIONS OF DATA

At times data were difficult to acquire as result of inadequate records or inaccessible, out-of-print publications. An explanation precedes each map describing the data limitations, sources of information and mapping technique. The amount of information available for a particular area of the State was usually proportional to the population density within the area and there was commonly little data available for sparsely populated areas.

Hydrogeologic Limitations for Subsurface Wastewater Injection

The criteria for evaluating the regional and site-specific hydrogeologic limitations for wastewater injection wells has been described by Warner and Lehr (December, 1979). Figure 1.1 represents an adaptation of the evaluation process outlined by the authors and is keyed to chapters, figures and tables in this report and plates and tables in the Hydrogeologic Atlas of Michigan.

Regional Evaluation

Characteristics of regions suitable for subsurface wastewater injection were described as follows:

- a. An extensive, thick sedimentary sequence should be present, to provide opportunity for an adequate injection interval and confining strata.
- b. Geologic structure should be relatively simple; that is, the region should be reasonably free of complex and extensive faulting and folding. Complex geologic structure complicates prediction and monitoring of waste travel and faults are possible avenues of wastewater escape.
- c. Possible injection intervals should contain saline water and should not be abundantly endowed with mineral resources (oil, gas, coal, etc.), so that the potential for degradation of natural resources is minimized.
- d. Fluid flow in possible injection intervals should be negligible or at low rates, and the region should not be an area of ground water discharge for the injection intervals being considered.
- e. The region should preferably not be one of high seismic risk, nor should it be a seismically active one. Earthquakes may damage injection facilities and, in seismically active area, injection may stimulate earthquakes.

Site Evaluation

Characteristics of suitable disposal sites and injection intervals were described as follows:

- a. Injection interval sufficiently thick, with adequate porosity and permeability to accept waste at the proposed injection rate without necessitating excessive injection pressures.

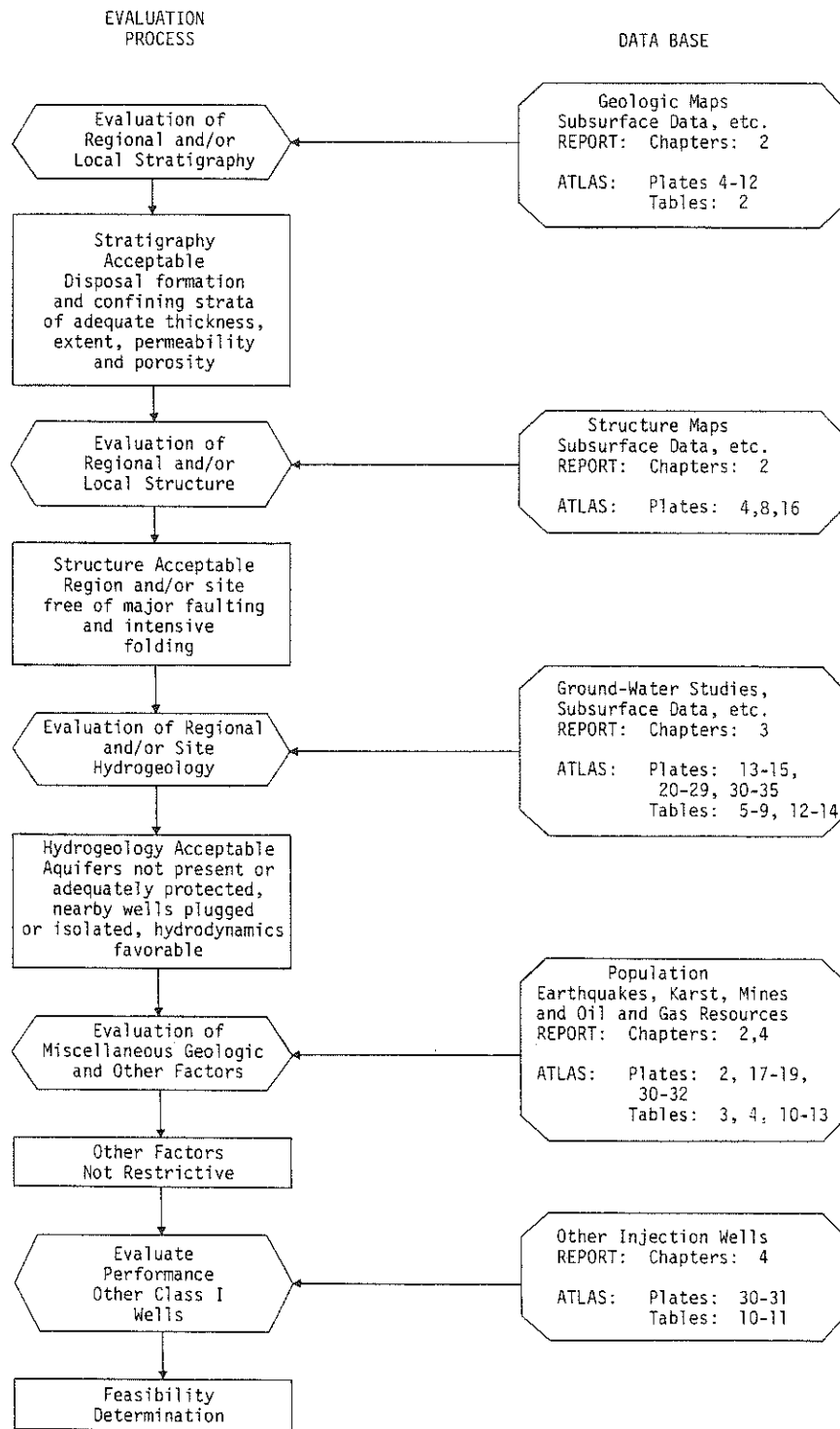


Figure 1.1. Evaluation Process for Subsurface Wastewater Disposal Through Class I Injection Wells (modified from Van Everdingen and Freeze, 1971).

- b. Injection interval of large enough areal extent so that injection pressure is minimized and so that injected waste will not reach discharge areas.
- c. Injection interval preferably "homogeneous" (without high-permeability lenses or streaks), to prevent extensive fingering of the waste-ys-formation water contact, which would make adequate modeling and monitoring of waste movement extremely difficult or impossible.
- d. Overlying and underlying strata (confining beds) sufficiently thick and impermeable, to confine waste to the injection interval.
- e. Structural geologic conditions generally simple, that is a site reasonably free of complex faulting and folding.
- f. Site is an area of minor to moderate earthquake damage and low seismic activity so that the hazard of earthquake damage or triggering of seismic events is minimized.
- g. Slow lateral movement of fluid in the injection interval, under natural conditions, to prevent rapid movement of waste away from the injection site, possibly to a discharge area.
- h. Formation-fluid pressure normal or low so that excessive fluid pressure is not needed for injection.
- i. Formation temperature normal or low so that the rates of undesirable reactions are minimized, including corrosion.
- j. Wastewater compatible with formation fluids and minerals or can be made compatible by treatment, emplacement of a buffer zone, or other means.
- k. Formation water in the disposal formation of no apparent economic value, i.e. not potable, unfit for industrial or agricultural use, and not containing minerals in economically recoverable quantities.
- l. Injection interval adequately separated from potable water zones, both horizontally and vertically.
- m. Waste injection not to endanger present or future use of mineral resources (coal, oil, gas, brine, others).
- n. Waste injection not to affect existing or planned gas-storage or freshwater-storage projects.

- o. No unplugged or improperly abandoned wells penetrating the disposal formation in the vicinity of the disposal site, which could lead to contamination of other resources.

Michigan Guidelines for Feasibility Studies

Preliminary studies related to the feasibility for subsurface disposal should address the following items:

1. Notice of Intent: Evidence that notice has been given to mineral owners within a two mile radius of the proposed well(s). These owners may waive right of protest. If the expected zone of influence of the proposed project is larger than two miles, then the area should be expanded accordingly.
2. Description of local topography, cultural features and human population in the area of the proposed disposal program and probable effects of the program on these factors.
3. Maps and cross sections illustrating detailed geologic structure and stratigraphic sections (formation, lithologic, and physical characteristics) for the local area and generalized maps and cross sections illustrating the regional geologic setting of the project.
4. A map indicating location of water wells and all other wells, mines, artificial penetrations (oil and gas wells, exploratory tests, etc.) showing depths and deepest formation penetrated, and their present condition within the expected area of influence of the proposed project. Exhaustive search shall be made to locate such penetrations. Well and abandonment records of the wells should accompany the map.
5. A map indicating vertical and areal extent of potable water supplies which would include surface water supplies and subsurface aquifers containing water with less than 10,000 ppm total solids, as well as available amounts and present and potential use of these waters.
6. The effect of this project on present or potential mineral resources in the area.
7. Description of the chemical, physical and biological properties and characteristics of the waste to be injected or disposed of. Relative alteration or stability characteristics of the wastes when exposed to time, pressures, temperature or other media.
8. Potentiometric surface maps of the injection aquifers and those aquifers immediately above and below the injection aquifer and copies of all drill stem tests, extrapolations and data used in making the maps.

- 9 Anticipated volume, rate, and injection pressure.
10. The following geological and physical characteristics of the injection interval and the confining units should be determined as accurately as possible and submitted by the owner along with the method of determination.
 - a. Effective thickness and areal extent (isopach map)
 - b. Lithology: Grain mineralogy, type and mineralogy of matrix, amount and type of cementing material, clay content and clay mineralogy.
 - c. Effective porosity (how determined).
 - d. Permeability, vertical and horizontal (how determined, or assumed, mechanical, radiation, electronic or other logs, core analysis, formation tests, etc.). Differentiation should be made between the relatively high permeability zones and the relatively low permeability zones and their comparative thicknesses.
 - e. Amount and extent of natural fracturing.
 - f. Location, extent and effects of known or suspected faulting.
 - g. Extent and effects of natural solution channels.
 - h. Fluid saturation.
 - i. Formation fluid chemistry (local and regional variations).
 - j. Temperature of formation (how determined).
 - k. Formation and fluid pressures (original and modifications resulting from previous fluid withdrawals).
 - l. Fracturing and fracture propagation gradients.
 - m. Osmotic characteristics of rock and fluids both comprising and contiguous to the reservoir.
 - n. Diffusion and dispersion characteristics of the waste and the formation fluid including effect of gravity segregation.
 - o. Compatibility of injected waste with the physical, chemical and biological characteristics of the reservoir.
 - p. Injectivity profiles.

- q. Expected changes in pressure, rate and direction of fluid displacement, by injected wastes relative to time, in area affected by the project.
11. The following engineering recommendations should be supplied if available at this time.
- a. Size of hole and estimated depth of well.
 - b. Type, size, weight, strength, etc. of all surface, intermediate, and production casing and accessory equipment.
 - c. Specifications and proposed installation of tubing and packers.
 - d. Proposed cementing procedures and type of cement.
 - e. Proposed coring program.
 - f. Proposed formation testing program.
 - g. Proposed logging program.
 - h. Proposed artificial fracturing or stimulation program.
 - i. Proposed completion procedure (open hole, perforated casing).
 - j. Plans of the surface and subsurface construction details of the system including a diagrammatic sketch of the system (pump, well head construction, casing depth, etc.).
 - k. Plans for monitoring injection, annular and formation pressures (injection well(s), observation well(s)).

This report will demonstrate that, on a regional basis and perhaps with the exception of item c, the Southern Peninsula of Michigan generally satisfies the above criteria; the Northern Peninsula does not. It follows that suitable sites exist in the Southern Peninsula, but are improbable in the Northern Peninsula.

The stratigraphy of Michigan is described in Part II of this report, Geology for Underground Injection: An Overview. Structure and thickness maps are included in the report, as well as the Hydrogeologic Atlas of Michigan, and lithologic units from the Precambrian through the Jurassic have been evaluated as aquifers, injection reservoirs and confining strata. Geologic structures of the Southern Peninsula are shown as interpreted by Prouty (1971) and faults and fault densities in the Northern Peninsula have been mapped from numerous Michigan and U.S. Geological Survey publications.

Part III of the report, Distribution and Occurrence of Potable Ground Waters in Michigan, assesses municipal, industrial and domestic water use, sources including glacial drift and bedrock aquifers, and quality of ground water in Michigan. The Atlas contains specially prepared maps of water well densities, bedrock wells, community supplies, water quality (total dissolved solids and specific conductance), and ground-water contamination sites. Of particular note are new maps of glacial drift thickness, vulnerability of the drift aquifer to contamination, and an interpretation of the glacial drift as an aquifer system.

Miscellaneous geologic factors including karst, earthquakes and mines are discussed in the report and mapped in the atlas. The history, geology and statistics of Class I, II and III wells are described and mapped in separate sections of the report and atlas. A system for estimating the potential for ground-water contamination from oil field brines was devised and the values displayed on maps in the atlas. Finally, maps of aggregate thickness of confining units (shales and evaporites) and isolation intervals were prepared to assist in determining the regional and site specific potential for underground injection.

ACKNOWLEDGEMENTS

We would like to acknowledge the many people who personally, or as members of organizations, assisted in many ways in the preparation of the report. Each map bears information regarding source of material and acknowledgements, but such comments do not adequately reflect the time generously given and the effort graciously and patiently expended.

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Great Lakes Basin Commission
Michigan Basin Geological Society
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United States Department of Energy

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Region II Planning Commission
Southcentral Michigan Planning Council
Southwest Regional Planning Commission
GLS Region V Planning and Development Commission
Tri-County Regional Planning Commission
East Central Michigan Planning and Development Region Commission
West Michigan Regional Development Commission
Northeast Michigan Council of Governments
Northwest Michigan Regional Planning and Development Commission
Eastern Upper Peninsula Regional Planning and Development Commission
Central Upper Peninsula Planning and Development Regional Commission
Western Upper Peninsula Regional Planning Commission
Western Michigan Shoreline Regional Development Commission

We would also like to thank the Kalamazoo businesses whose assistance and patience facilitated our efforts.

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- 4) Warner, C.L., and Lehr, J.H., 1977, An introduction to the technology of subsurface wastewater Injection: Municipal environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio, EPA-600/2-77-240, 345 p.

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Geology of Bedrock Units

PRECAMBRIAN

Precambrian rocks that outcrop in the western Northern Peninsula have been variously classified, but most authors have recognized a three-fold subdivision (figs. 2.1, 2.2 and 2.3, pls. 4,5 and 6). At present, an accepted manner of classifying Precambrian rocks is to assign them to a lettered series based on age (W,X,Y and Z). Applying this system to the outcropping Precambrian rocks of Michigan reflects the three divisions recognized by earlier workers as many workers have placed the Jacobsville (Precambrian Z) in the Cambrian System.

The oldest rocks in Michigan, designated Precambrian W comprise a sequence of mafic volcanics that were intruded by felsic plutons and subsequently metamorphosed to schists and gneisses.

Precambrian X rocks, shown by field relationships to be younger than the oldest rocks, consist mainly of metasedimentary rocks formed by the metamorphism of shales, sandstones, carbonate rocks and iron formations. These quartzites, marbles, slates and iron-rich rocks were intruded by basic igneous rocks during periods of intense folding. Although the intrusive rocks have been transformed to metadiabase they retain dike- and sill-like relationships to the enclosing rocks.

Characteristics as an Aquifer. Precambrian W and X rocks are known to produce water from fractures. The spacing and width of such fractures is strongly a function of depth. In general, fractures are widest and most numerous at the land surface and become narrower and less abundant with depth. Moreover, wells deeper than about 400 feet may yield water too salty for domestic use.

In areas where bedrock is at or near the land surface most borings fail to yield sufficient water for a modern domestic supply. In localities where bedrock is overlain by 20 feet or more of permeable drift, wells generally yield small supplies with a few wells producing as much as 20 gallons per minute. Although specific capacities as high as 5 gpm per foot of drawdown have been reported most wells produce less than 1 gpm per foot of drawdown (Doonan and Hendrickson, 1966). Because fracture spacing increases and dilation decreases with depth, it usually futile to drill deeper than 100 feet into Precambrian W and X rocks in search of water (Doonan and Hendrickson, 1966).

Characteristics as a Confining Layer. Most of the igneous and metamorphic rocks that comprise the complex terrane underlain by Precambrian rocks lack effective porosity and permeability. These

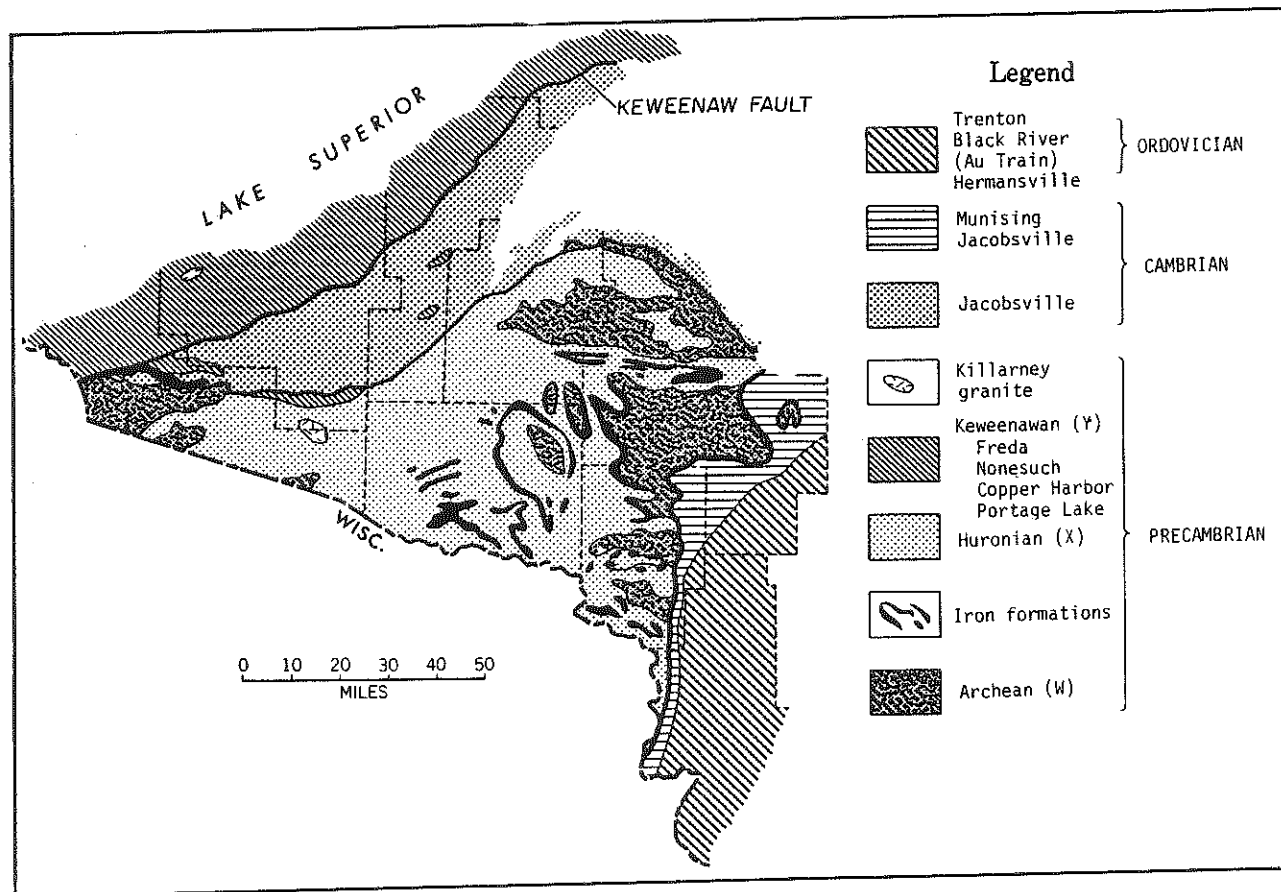
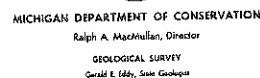


Figure 2.1. Generalized geologic map of the Central and Western Provinces of the Northern Peninsula of Michigan. (Modified from Dorr and Eschman, 1970.)

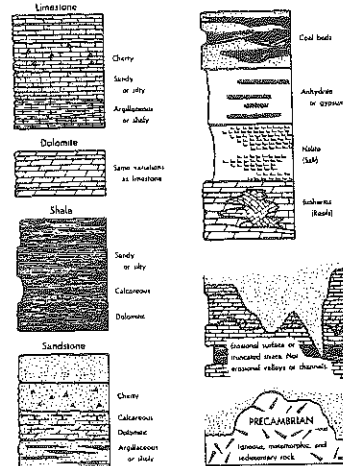
PALFOZOIC THROUGH RECENT



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INFORMAL TERMS

EXPLANATION



GEOLOGIC NAMES COMPILATIONS. Harry O. Sorenson. Cambrian and Ordovician, Robert W. Kelley. Early and Middle Silurian. Garland D. Ellis. Late Silurian through Devonian. Group of Devonian age, Harry J. Herdendorf. Dundee Limestone through Pennsylvanian. Group of Devonian age, L. David Johnson. Antenn Shale through the Pennsylvanian System, F. Wells Terwilliger. glacial geology of the Colorado.

CHART 1
1964

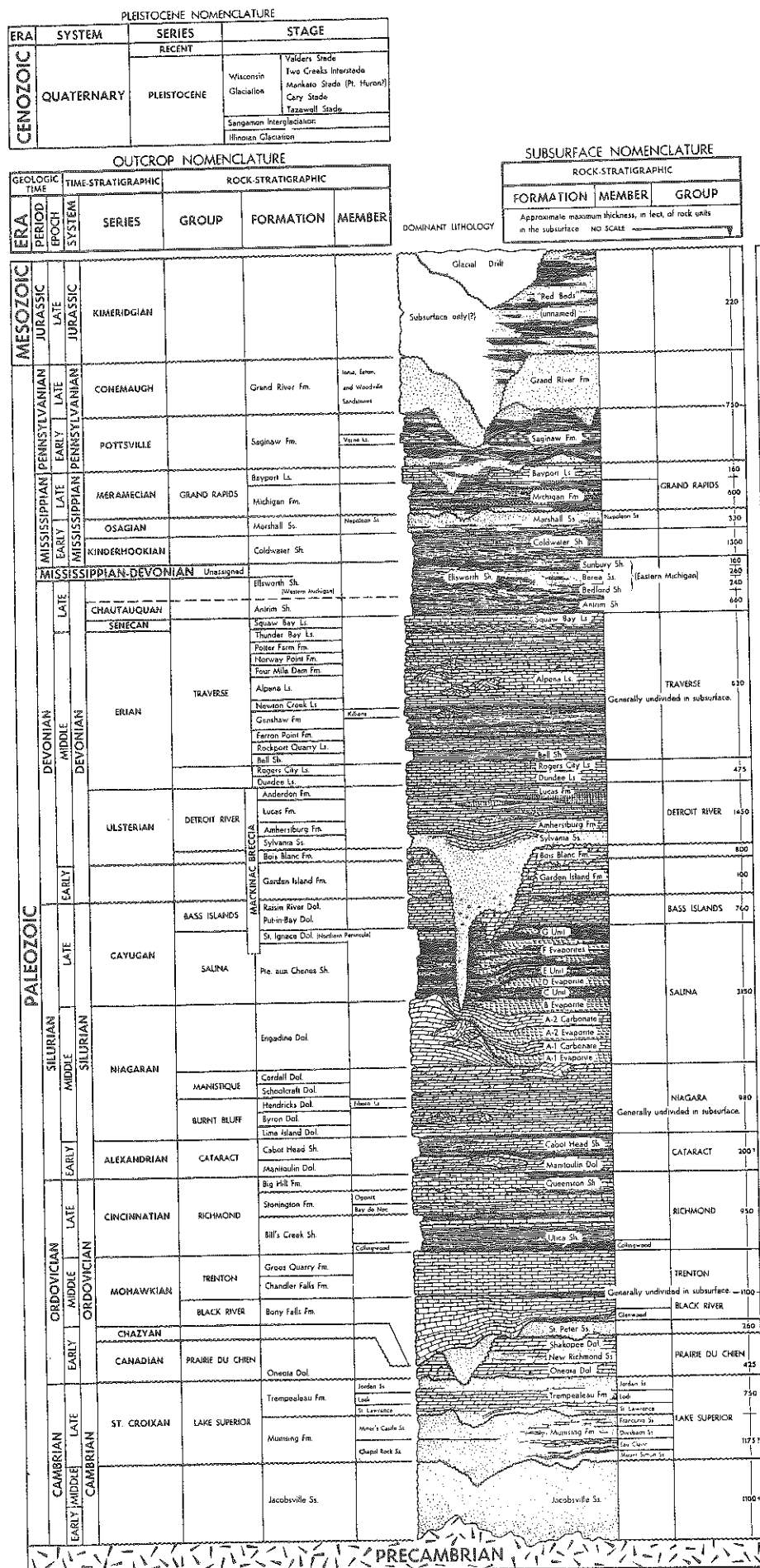
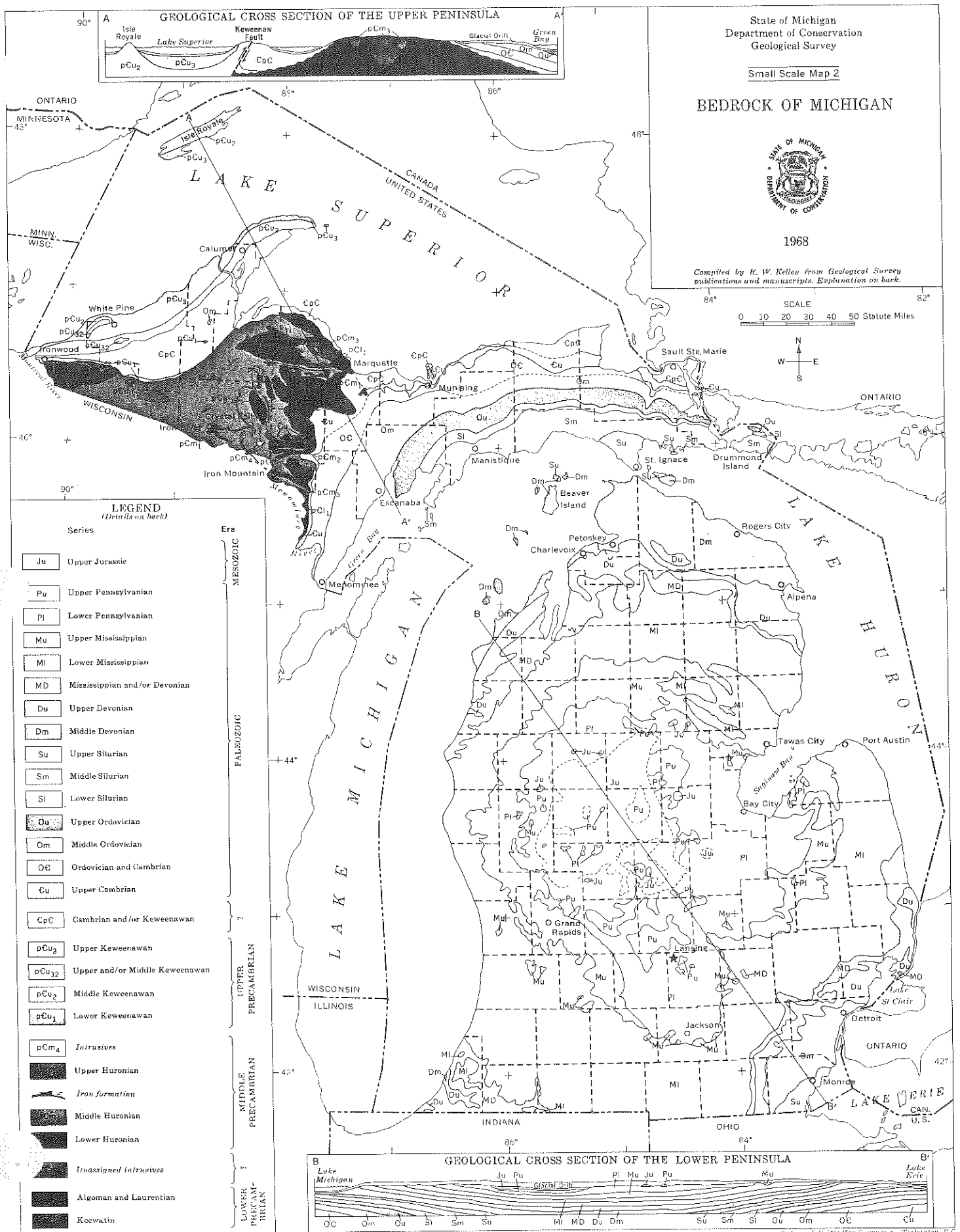


Figure 2.3. Geologic map of Michigan.



lithologies do transmit water through fractures. In general, fractures are only present in the upper 300 feet of the rock column, some fractures have been shown to extend to great depth. Consequently, Precambrian W and X rocks should not be considered as containment rocks unless detailed study of an area shows them to be free of fractures that extend to great depth.

Porosity. Except where fractured, Precambrian W and X rocks lack effective porosity.

Permeability. Except where fractured these rock types are essentially impermeable.

Oil and gas potential. None

Precambrian Y

Precambrian Y rocks (Keweenaw) consist of a thick volcanic sequence, the Portage Lake Lava series, volcano-clastic sediments derived from them, and a few felsic intrusions. Although the age of the overlying Jacobsville Sandstone is uncertain, many geologists consider it to be Precambrian Y.

The Middle Keweenaw Portage Lake Lava Series and the Upper Keweenaw Copper Harbor Conglomerate, Nonesuch Shale and Freda Sandstone. Middle and Upper Keweenaw rocks outcrop or subcrop beneath the glacial drift in a northeast-trending belt 4 to 12 miles wide in the westernmost portion of the Northern Peninsula in Gogebic, Ontonagon, Houghton, and Keweenaw Counties (Doonan, et al., 1970). The area of outcrop is essentially the northwestern half of the Keweenaw Peninsula. Structurally, the rocks in this area comprise the southeast limb of the Lake Superior (Keweenaw) syncline and dip to the northwest beneath Lake Superior. Major stratigraphic units thicken downdip toward the center of the basin and away from a former source area to the southeast. There is no evidence of regional metamorphism having affected these units (Spiroff and Slaughter, 1961).

In Houghton and Keweenaw Counties, the Middle Keweenaw Portage Lake Lava Series consists of several hundred basalt and andesite flows which, with interbedded conglomerates, reach a maximum thickness of approximately 15,000 feet in Keweenaw County. Dips range from 25 to 75 degrees northwest and decrease to the northwest away from the Keweenaw Fault. On Isle Royale, dips are 15 to 25 degrees to the southeast.

The basal unit of the Upper Keweenaw, the Copper Harbor Conglomerate, overlies the Portage Lake Lava Series. It ranges in thickness from 2300 to 5500 feet and consists of light red to brown cemented, non-porous boulder conglomerates and minor pebble conglomerates and arkosic sandstones that dip 25 to 30 degrees northwest. In Keweenaw County and northern Houghton County, the Copper Harbor Conglomerate consists of a conglomerate with overlying and underlying lava flows

(Lakeshore Traps) that pinch-out south of Township 55 North. The Copper Harbor Conglomerate outcrops or subcrops beneath the glacial drift in a narrow band 1 to 3 miles wide from Keweenaw Point at the north to Rockland in Ontonagon County on the south.

The Nonesuch Shale conformably overlies the Copper Harbor Conglomerate. It averages about 600 feet in thickness and dips 19 to 20 degrees to the northwest. In Ontonagon County, it is mostly a gray siltstone. Throughout its northeasterly trending outcrop, the Nonesuch is quite uniform in thickness and appearance. The Lower 20 to 25 feet of the Nonesuch is a copper-bearing zone that is mined at the White Pine Copper Mine (Spiroff and Slaughter, 1961).

The Freda Sandstone conformably overlies the Nonesuch Shale and consists of alternating 3 to 4 foot layers of fine-grained arkosic sandstone and red micaceous silty shale. Pebble conglomerates are common and reach 150 feet in thickness. The lower 1500 feet is generally more coarsely grained than the upper portion. Ripple marks, mud cracks and other features attest to shallow water deposition (Spiroff and Slaughter, 1961).

Houghton and Keweenaw Counties. Bedrock crops out in large areas of Keweenaw and northern Houghton counties beneath a thin glacial cover. Low permeability of the glacial drift generally necessitates bedrock wells. Most ground-water supplies in Houghton and Keweenaw Counties are obtained from wells 100 to 200 feet deep. About half the wells in Houghton County and most in Keweenaw County produce from bedrock and are cased through the glacial drift into bedrock. Several wells on the northern edge of Keweenaw County obtain small to moderate supplies of water from the Copper Harbor Conglomerate. Yields up to 12 gpm are obtained from the Copper Harbor Conglomerate in Houghton County. A few wells in the Portage Lake Lava Series produce small supplies. Due to small yields, only a few wells in Houghton and Keweenaw Counties obtain water from the Nonesuch and Freda Sandstones. Water from most wells is satisfactory for domestic use and most municipalities use ground water which is generally soft to moderately hard. Yields are generally less than 10 gpm with some over 20 gpm (Doonan, et al., 1970). Salinity tends to increase with depth and wells greater than 300 feet deep in the Portage Lake Lava Series may be too salty for domestic use. About one-third of the wells contain iron in excess of 0.3 mg/l.

Ontonagon County. The glacial drift is a poor aquifer in Ontonagon County. It is generally less than 300 feet thick and consists dominantly of clay or sandy clay lake sediments overlying till, clay tills of moraines, and stratified sand and gravels of outwash plains and valley trains. About 60 percent of the wells produce from fractures in bedrock. Because yields depend on the number and size of the fractures penetrated, the best production is from the upper 50 feet and decreases with depth.

Where the Freda outcrops, most wells produce from this formation at depths of 30 to 325 feet, generally less than 150 feet. Yields vary greatly within short distances, but are generally satisfactory for household needs. Near Lake Superior, water from bedrock aquifers greater than 75 feet deep is high in chlorides and iron. About half the wells in the outcrop area of the Nonesuch, Copper Harbor Conglomerate, and Portage Lake Lava Series produce from bedrock. Most wells are over 200 feet deep and yields are adequate for household purposes, but some are high in chlorides and iron. The interbedded lava flows, sandstones, shales, and conglomerates of the Porcupine Mountain area are generally unfavorable for obtaining water. Thus, although quantities suitable for domestic wells are common, large supplies of ground water are unknown from bedrock in Ontonagon County (Doonan and Hendrickson, 1969).

Gogebic County. In contrast to Keweenaw, Houghton, and Ontonagon Counties, nearly all wells in Gogebic County produce from the glacial drift and only a few from bedrock. Over 90 percent of the municipal and domestic water use is from ground water. Production is mainly from glacial sands and gravels with most large wells producing from stream gravels. Bedrock production is from fractures. Most wells are 50 to 100 feet deep and generally are not successful below 200 feet.

Characteristics as an Aquifer. The Keweenawan Series produces water from fractures and fracture zones. Production is greatest where thick, water-bearing glacial materials are present. In general, wells completed below 400 feet produce water that is too salty for domestic or commercial use.

Characteristics as a Confining Layer. The Portage Lake Lava Series, Copper Harbor Conglomerate, Nonesuch Shale, and Freda Sandstone are fractured and generally unsuitable as confining layers.

Characteristics as an Injection Formation. The Portage Lake Lava Series, Copper Harbor Conglomerate, Nonesuch Shale, and Freda Sandstone are unsuitable as injection formations due to their low permeability, fractured nature, and importance as aquifers.

Porosity. Porosity is low and primarily due to fractures.

Permeability. Permeability is low and primarily the result of fractures. It generally decreases with depth. Well yields are generally less than 20 gpm.

Oil and Gas Potential. Hydrocarbons have been found in the Nonesuch Shale, but these rocks offer little potential for commercial production of oil and gas.

Precambrian Z

Jacobsville Sandstone. The age of the Jacobsville is unknown. Although it has been previously assigned a Cambrian age (Hamblin, 1958; Ostrom & Slaughter, 1967), the U.S. Geological Survey (1974) has mapped it as Precambrian Z.

The Jacobsville Formation is widely distributed in the Northern Peninsula, extending from outcrops along the St. Mary's River in the eastern Northern Peninsula (Landes, 1942) to Gogebic County in the western Northern Peninsula (fig. 2.4, pl.6). Exposures are abundant along the Lake Superior shoreline from Munising to west of Marquette and along the shores of Keweenaw Bay. A broad outcrop and subcrop band extends southwestward from the head of Keweenaw Bay through portions of Baraga, Houghton, Ontonagon, and Gogebic Counties.

The Jacobsville has a wide range of thickness because of the significant relief on the Precambrian surface upon which it was deposited (Hamblin, 1958). In many places along its southern margin it pinches out completely against a former Precambrian highland which served as a major source for the sediment composing the formation. Thicknesses up to 300 feet have been measured in exposures along the Lake Superior shore and in Chippewa County a well penetrated a thickness in excess of 1800 feet.

Catacosinos (1973) reported that a well on Beaver Island (State No. 1) penetrated the Mt. Simon into 813 feet of pale reddish-purple sandstones, siltstone, and shale. The sandstones are dominantly coarse-grained quartz, with much feldspar that is silica-cemented, abundant hematite staining, and some glauconite. Catacosinos (1973) suggested that a downthrown fault block was responsible for preserving this isolated occurrence of Pre-Mt. Simon rocks. The stratigraphic position of this unit below the Mt. Simon and above the Precambrian suggests a possible correlation with the Jacobsville. The units are similar in lithology and stratigraphic position, but the presence of glauconite indicates a marine origin (Catacosinos, 1973) rather than the non-marine origin ascribed to the Jacobsville by Hamblin (1958).

The Jacobsville is mostly reddish to reddish-brown friable feldspathic quartz sandstone with intercalated lenses of red or gray conglomerate and reddish shale. Hamblin (1958) recognized four distinct units which he designated as facies. From bottom to top these are: 1) conglomerate facies, 2) lenticular sandstone facies, 3) massive sandstone facies, and 4) red siltstone facies.

Characteristics as an Aquifer. In the western Northern Peninsula the Jacobsville is widely used as a bedrock aquifer and is the most reliable source of ground water in Baraga County (Doonan, Byerly, 1973). Most wells yield enough water for domestic use; but, some have yielded salty water and were abandoned. In Baraga County most

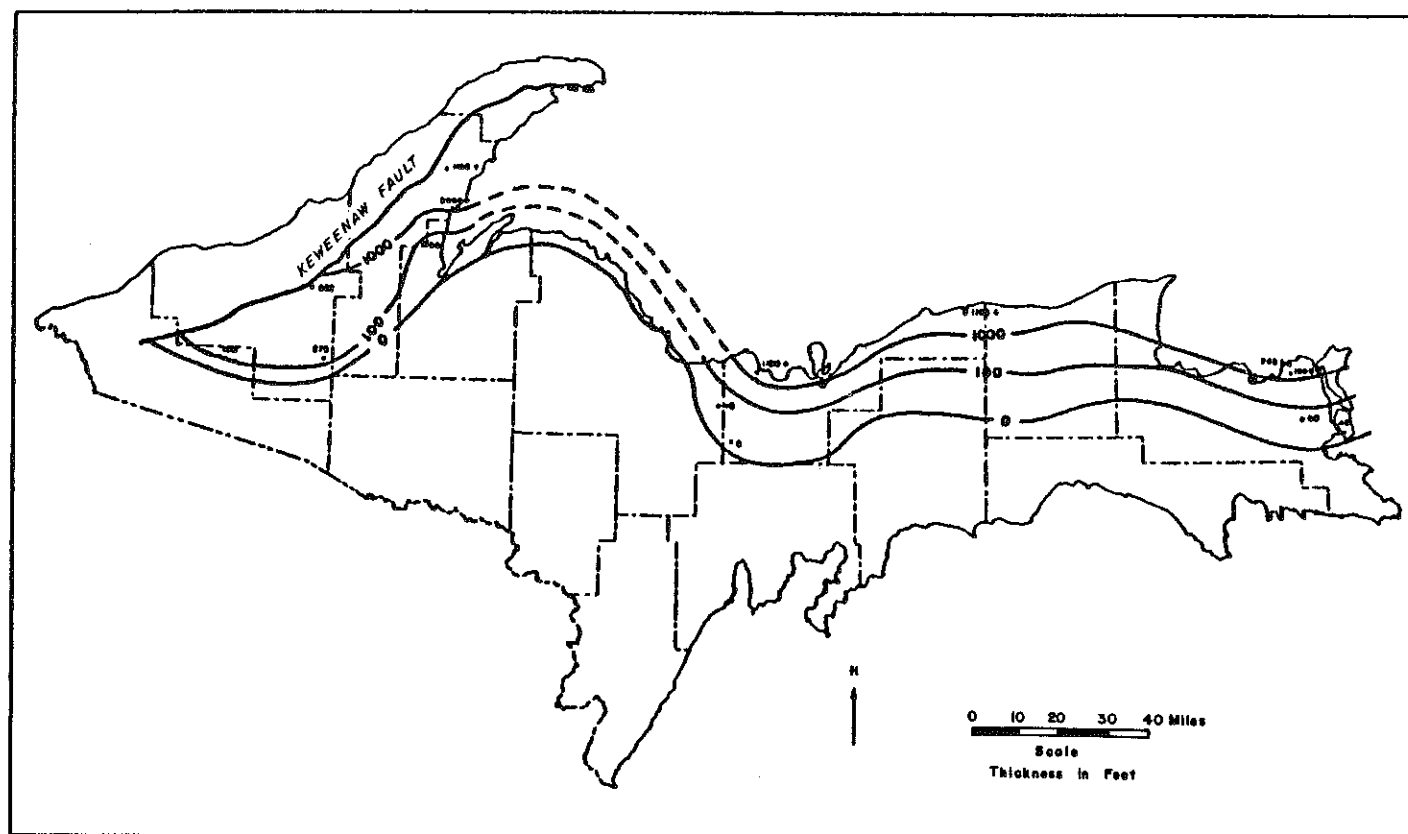


Figure 2.4. Thickness of Jacobsville Formation. (From Hamblin, 1958.)

wells are 100 to 300 feet deep and penetrate 50 to 250 feet of sandstone. Water occurs along open fractures which tend to decrease in number and size with depth. Permeability, consequently, tends to decrease with depth. Yields in Baraga County range from 1.5 to 50 gpm with specific capacities from 0.01 to 2.5 gallons per minute per foot of drawdown.

Water quality for domestic use is generally satisfactory, although most wells yield water that is moderately hard to very hard with calcium carbonate ranging from 36 to 520 mg/l, and iron content from 0.1 to 5.0 mg/l (Doonan, Byerley, 1973).

Characteristics as a Confining Layer. Fracture and intergranular porosity and permeability preclude use of the Jacobsville as a confining layer.

Characteristics as an Injection Formation. The Jacobsville has some intergranular porosity and permeability. It seems likely that down dip from the outcrop area the unit may be sufficiently permeable to accept fluids. Because sandstones of the Munising Group, an aquifer, directly overlie it the Jacobsville should not be used as an injection formation in the Northern Peninsula. The unit may have some potential if it is found to underlie the Mt. Simon Sandstone.

Porosity. The coarse-grained facies, conglomerate and sandstone, have some intergranular porosity. Available information are insufficient to determine whether such porosity increases away from the outcrop area. Fracture porosity is greatest near the exposed surface of the unit and decreases with depth.

Permeability. Permeability in the Jacobsville is related to fracturing. Fracture frequency and dilation diminish with depth and there is a concomitant decrease in permeability.

Oil and Gas Potential. The Jacobsville is not productive of oil and gas and no shows have been reported from it. Consequently, the potential for hydrocarbon reserves in the unit are very low.

PALEOZOIC

CAMBRIAN

Cambrian rocks in the subsurface of the Southern Peninsula (figs. 2.5 and 2.6, pls. 6,7 and 8, Strat. Col. & Cross Sections) cover an area of 150,000 sq km (60,000 sq mi) (Catacosinos, 1973). They do not outcrop in the Southern Peninsula. Catacosinos reported that through July, 1972 only 140 (0.5 percent) of the 30,000 oil and gas wells drilled in Michigan penetrated Cambrian rocks. The Cambrian and Cambro-Ordovician stratigraphic nomenclature used in this report is shown in table 2.1 and 2.7.

TABLE 2.1 - CAMBRIAN AND CAMBRO-ORDOVICIAN STRATIGRAPHY OF THE SOUTHERN PENINSULA OF THE MICHIGAN BASIN (modified from Catacosinos, 1973)

	Southern Peninsula		Northern Peninsula
	Southwest	Central and Northern	
ORDOVICIAN		Jordan Formation (0-600+)	
-----	St. Lawrence Fm.	(St. Peter Sandstone)	Au Train
CAMBRIAN		Lodi Formation (0-150+)	
Late Cambrian		Munising Group (0-1700+)	Munising Formation
		Franconia Formation (0-700+)	Miners Castle Sandstone
		Galesville Sandstone (0-180)	?
		Eau Claire Formation (0-700+)	Chapel Rock Sandstone
		Mt. Simon Sandstone--?- (0-1000+)	unnamed sandstone
		--?-	Jacobsville Sandstone

Mt. Simon Sandstone

The Mt. Simon Sandstone lies unconformably upon underlying rocks in Michigan and grades upward and interfingers with the overlying Eau Claire (Catacosinos, 1973). It is widely distributed in the subsurface of the Southern Peninsula of Michigan (Catacosinos, 1973). Although it has not been positively identified in the Northern Peninsula, an unnamed, poorly consolidated sandstone with sporadic occurrences above the Jacobsville

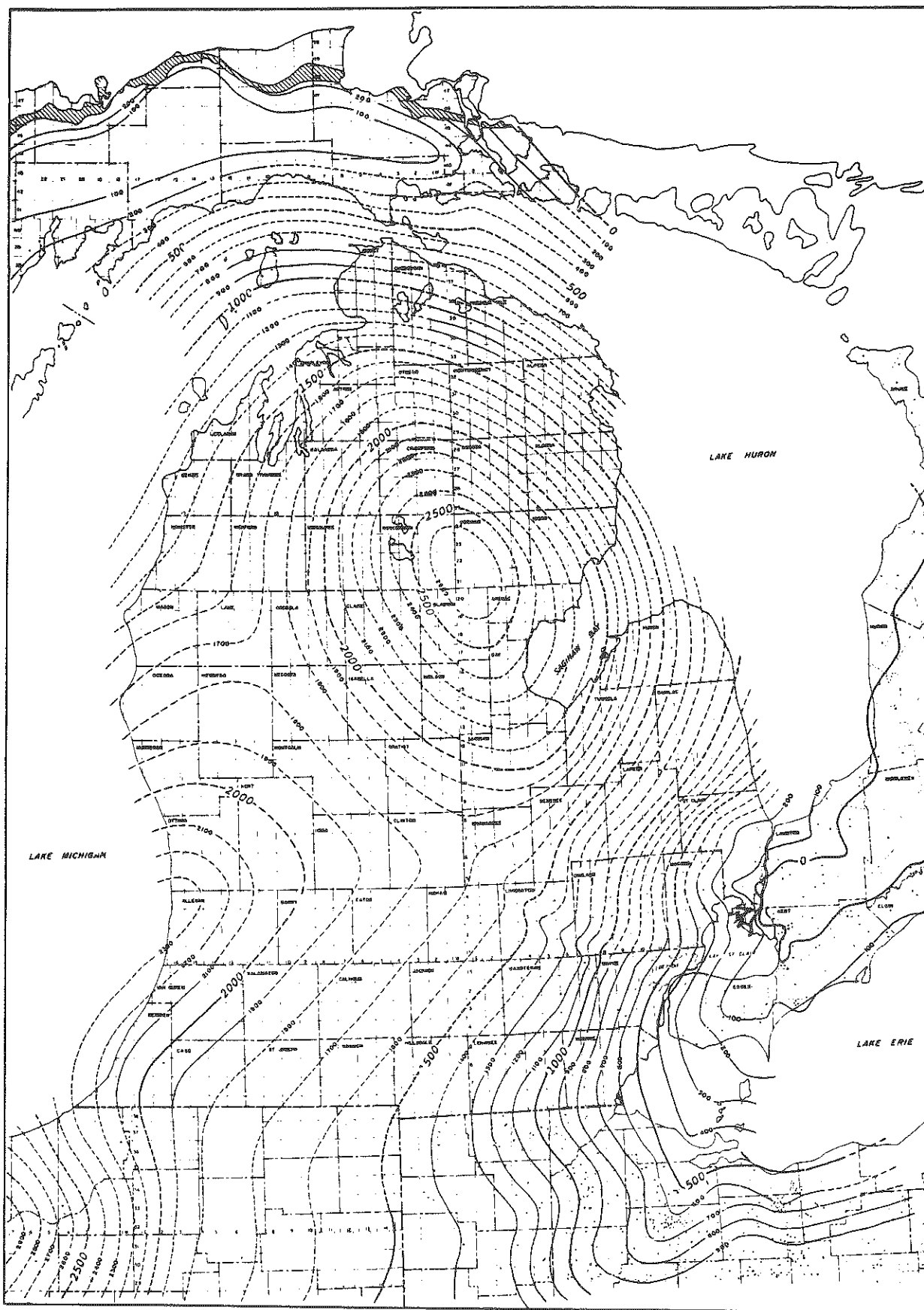


Figure 2.5. Thickness of Cambrian system. (From Fisher, in Michigan Basin Geological Society, 1969.)

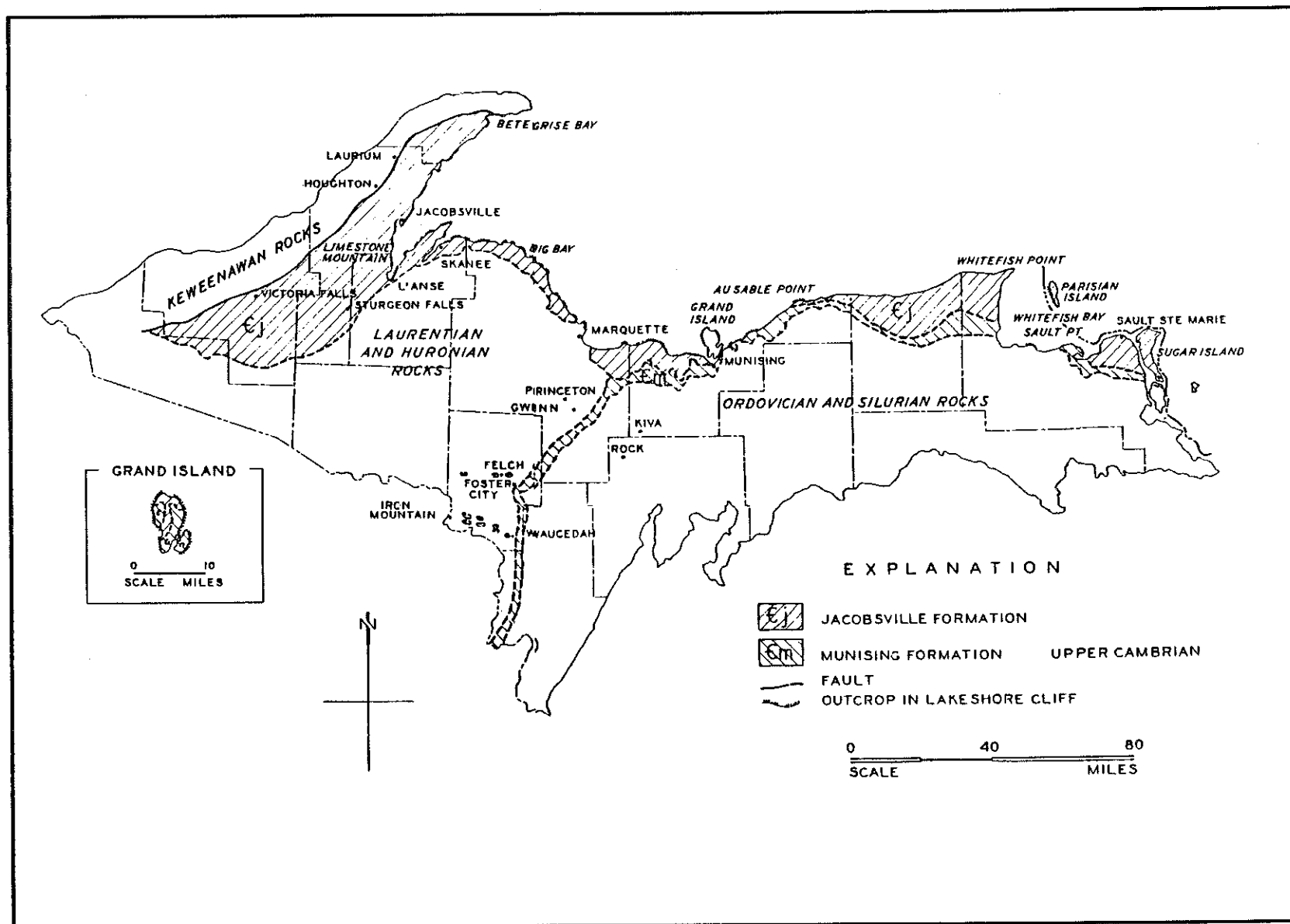


Figure 2.6. Geologic map showing the distribution of the Jacobsville Sandstone and Cambrian rocks in Northern Michigan. (From Hamblin, 1958.)

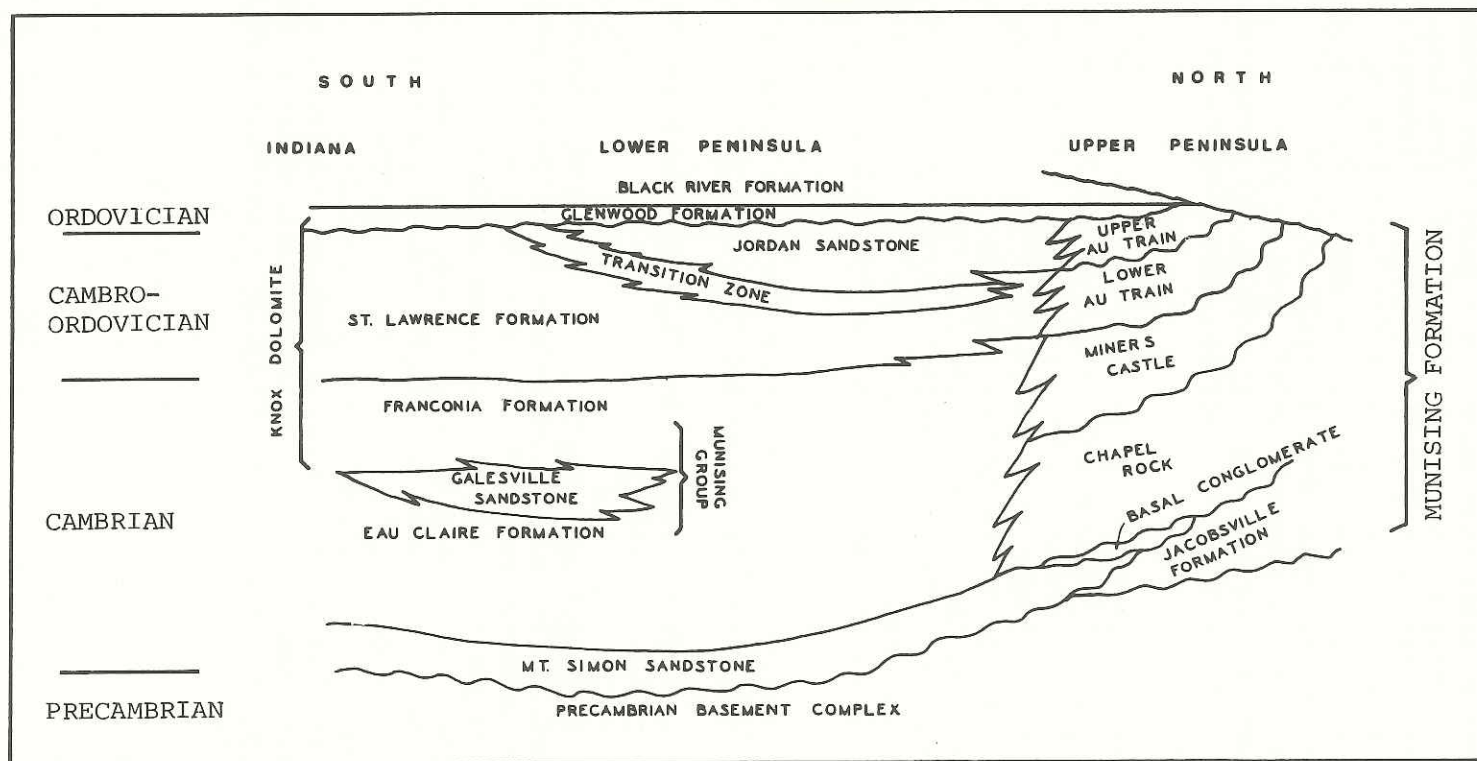


Figure 2.7. Idealized cross section showing Cambrian and Cambro-Ordovician stratigraphy. (Adapted from Catacosinos, 1973.)

and below the basal conglomerate of the Munising may be Mt. Simon (Cohee, 1945; Driscoll, 1959; Catacosinos, 1973). The Mt. Simon thickens southwestward from a line between Munising in the Northern Peninsula and Alpena in the Southern Peninsula (fig. 2.8) to approximately 1000 feet in the extreme southwest corner of the Southern Peninsula. The Formation is apparently absent in a local area in southeastern Michigan, but according to Catacosinos (1973), 877 feet have been recorded in Berrien County in southwestern Michigan. Although the age of the Mt. Simon is uncertain because of its indistinct stratigraphic position and lack of fossils, Catacosinos (1973) placed it in the Late Cambrian, but suggested that it might be Middle Cambrian (table 2.1). Ostrom and Slaughter (1967) have suggested that the Mt. Simon is correlative with the Jacobsville, but Catacosinos (1973) did not believe that the criteria described were adequate to support this conclusion.

In Michigan the Mt. Simon is characterized by subrounded to rounded quartz grains that are generally coarse and range from medium to very coarse. Typically, it is cemented with silica and contains little or no glauconite. Catacosinos (1973) used the absence of glauconite to separate the overlying series of glauconitic sandstones from the Mt. Simon. The unit is pinkish or reddish at the base and light pink near the top indicating an upward decrease in hematite content. Also, the base of the unit contains a greater abundance of feldspar grains. Glauconite, anhydrite, and green shale are present in minor amounts with local dolomite cement.

Characteristics as an Aquifer. The Mt. Simon Sandstone contains brine throughout the Southern Peninsula and is not an aquifer.

Characteristics as a Confining Layer. The Mt. Simon Sandstone is too permeable to be a confining layer.

Characteristics as an Injection Formation. The permeable Cambrian quartzose sandstones, siltstones and arenaceous dolomites suitable for fluid injection comprise about 27% of the stratigraphic column in southeastern Michigan and outcrop only in the Northern Peninsula (Briggs et al., 1968). According to Briggs (1968) the receptivity of the sandstones in the Mt. Simon is moderately high if the rock is treated with acid and hydraulically fractured. A disposal well, the Consumers Power Company Brine-Disposal Well No. 149, Sec. 39, T. 4N., R. 15E., in St. Clair County, southeastern Michigan accepted 2 million gallons of salt water a month at an injection pressure of 825 p.s.i. Briggs suggested that the Mt. Simon may constitute a reservoir with an immense capacity for fluids.

Porosity. Information regarding porosity of the Mt. Simon is restricted to a few wells that have penetrated this unit. Analysis of a core taken from a well in St. Clair County revealed porosities of 4 to 20 percent. According to Briggs (1968) a wide range of porosities exist within this unit and there is no discernable trend with depth. Porosity decreases where sandstones grade laterally into carbonate facies.

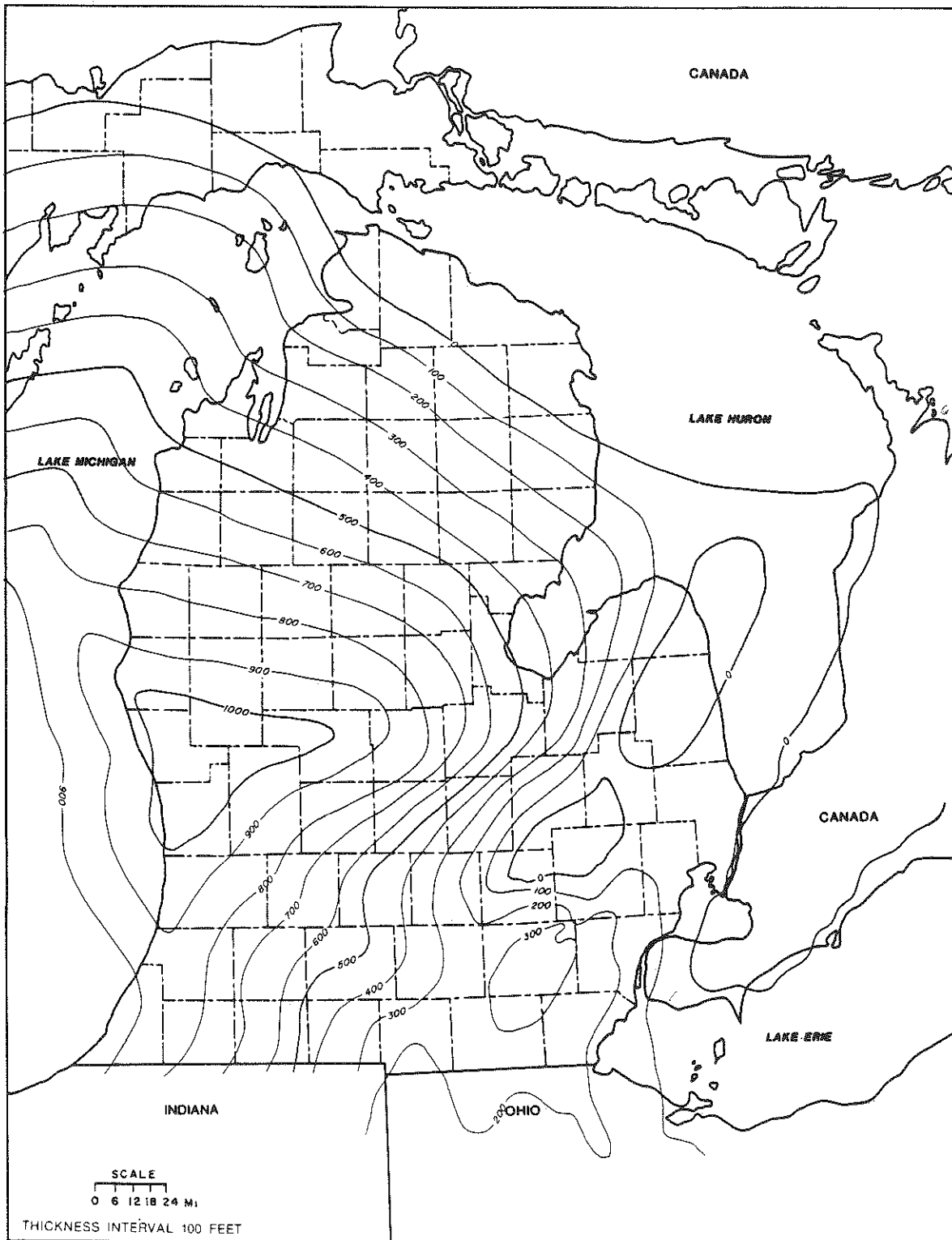


Figure 2.8. Thickness of Mount Simon Sandstone. (From Catacosinos, 1980.)

Permeability. A wide range of permeabilities exist within the Mt. Simon. Greatest permeabilities occur in well-sorted coarse sands and lowest permeabilities are in carbonate cemented units. Average permeability determined for the core from the St. Clair disposal well was 32 millidarcies.

Oil and Gas Potential. The Mt. Simon has not been extensively explored for hydrocarbons in the Michigan Basin. No production has been reported, but the unit must be considered an exploration target.

Munising Group (Northern Peninsula)

In the Northern Peninsula the Munising consists of three members; an unnamed basal conglomerate, the Chapel Rock Member, and the Miner's Castle Member (Hamblin, 1958). The formation is well exposed in a series of prominent cliffs along the Lake Superior shoreline east of Munising (figs. 2.7, 2.9, pl. 9).

The basal conglomerate member is a widespread orthoquartzitic conglomerate reaching a maximum thickness of 15 feet (Hamblin, 1958). Vein quartz, quartzite, and chert constitute over 90 percent of the well-rounded pebbles and cobbles making up the conglomerate. The average clast diameter is 2 to 3 inches; however, some cobbles approach 12 inches.

The Chapel Rock Member consists of well-sorted, medium-grained sandstone with large scale cross-bedding. Along the Pictured Rocks and throughout most of Alger County it is from 40 to 60 feet thick. The sandstone is composed almost entirely of quartz, quartzite, and chert grains with minor amounts of feldspar (Hamblin, 1958). Many small angular quartz fragments form a matrix for the larger grains serving as a clastic binder. Calcium carbonate is locally abundant near fractures; however, in most places silica is the dominant cementing material.

The Miner's Castle Member is the most widespread unit forming the upper 140 feet of the Munising Formation. It consists of poorly sorted, cross-bedded sandstone with very little lateral variation throughout the outcrop belt. Quartz grains constitute over 95 percent of the rock with minor amounts of feldspar and chert. Although secondary quartz is the major cementing agent the rock generally remains porous and friable. An exception occurs in Dickinson County where, locally, secondary quartz fills the interstices and produces a very hard orthoquartzite. In places, authigenic pyrite occurs in appreciable amounts in the middle of the Miner's Castle Member. The grain size ranges from pebbles to silt and clay. These extreme variations largely occur between sedimentation units. Sorting is much better in the upper part of the Miner's Castle which is relatively free of shale and conglomerate (Hamblin, 1958).

Characteristics as an Aquifer. As an aquifer, the members of the Munising Group are not differentiated. Moreover, because the overlying Au Train Formation is thought to be hydraulically connected with the Munising, these units are usually considered to

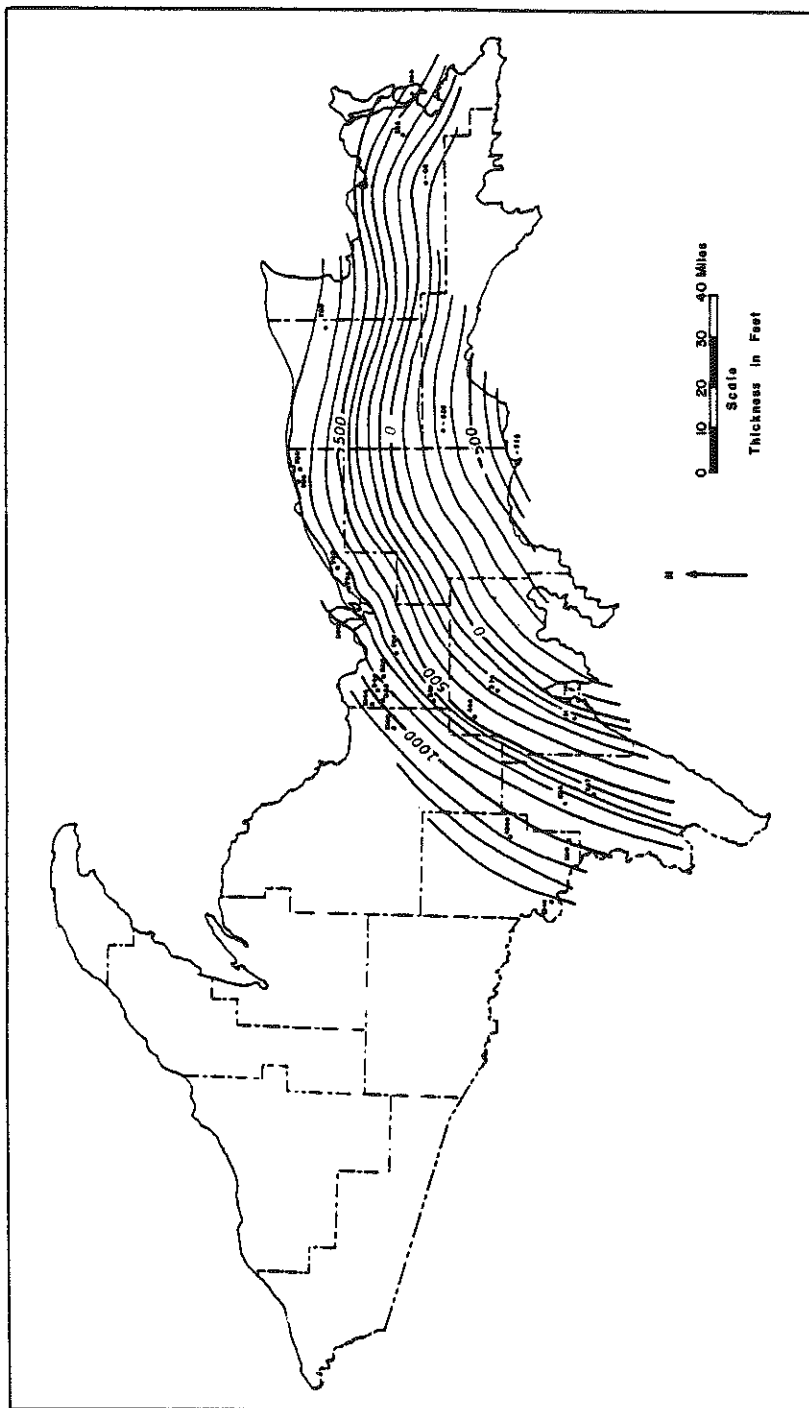


Figure 2.9. Structure contours on the top of Munising Formation. (From Hamblin, 1958.)

form a single aquifer. Locally, as along the Lake Michigan shoreline in Alger County, wells in this aquifer flow at the surface. Recharge to this system is apparently at the outcrop or from the overlying drift.

The Munising-Au Train aquifer is an existing or potential aquifer throughout the eastern Northern Peninsula. Water quality information indicates that water in this system has a low dissolved solids content near the outcrop area, and that the dissolved mineral content increases downdip.

Locally, along the downdip margin of the Peninsula the unit may contain objectionable concentrations of dissolved minerals although known occurrences of saline water may be due to inadequate well completions that permit saline water from overlying formations to mix with water from the Munising-Au Train system (Sinclair, 1959).

Characteristics as a Confining Layer. The Munising is far too permeable to serve as a confining layer.

Characteristics as an Injection Formation. The Munising Group is an aquifer or potential aquifer throughout its area of occurrence in the eastern Northern Peninsula and should not be used as an injection formation.

Porosity. Sandstones of the Munising-Au Train aquifer system have intergranular porosity that ranges from low to moderate depending upon the degree of cementation. At and near the outcrop and subcrop area, the system has varying degrees of fracture porosity. Dolomitic units within the system contain water along solutionally enlarged bedding surfaces.

Permeability. Permeability of rocks in this aquifer is dependent upon the degree of cementation and the presence of fractures which are numerous near the outcrop. Most of the sandstones have moderate permeabilities (Sinclair, 1959).

Oil and Gas Potential. Although rocks equivalent to the Munising-Au Train are targets for hydrocarbon exploration in the Southern Peninsula, it is unlikely that they will produce oil or gas in the Northern Peninsula. Recent discoveries in the central Southern Peninsula are apparently from rocks correlative with part of this system (Oil and Gas News, 1981).

Munising Group (Southern Peninsula)

In the Southern Peninsula, Catocsinos (1973) has raised the Munising to group status and redefined it to include the Eau Claire, Galesville, and Franconia formations (table 2.1, fig. 2.7, pl. 9). The Eau Claire and Franconia are lithologically similar and can only be distinguished where separated by the Galesville; therefore, where the Galesville is absent the term Munising Group is used.

The Munising Group shows distinct basinal characteristics and establishes the structural development of the Michigan Basin as being as early as Late Cambrian time (Catacosinos, 1973). The maximum thickness of the Group is approximately 1700 feet near the center of the Basin (fig. 2.10). A deep test well in Ogemaw County penetrated 1417 feet of thin bedded and nodular anhydrite. The lateral extent of this anhydrite facies is unknown and some controversy exists over the age of this sequence; however, Catacosinos (1973) has informally called it the anhydrite member of the Munising Formation.

Eau Claire Formation

The Eau Claire Formation overlies the Mt. Simon Sandstone in the southern part of the Southern Peninsula. This unit consists of a lower sandstone that is commonly included with the Mt. Simon and an upper section of thinly bedded siltstones.

The Eau Claire appears to be thickest (700 feet) in a small, basinal area centered near Calhoun and Kalamazoo Counties. North of the northernmost extent of the Galesburg, the Eau Claire probably comprises the bulk of the Munising Formation which ranges in thickness from 0 feet at the northern edge of the Southern peninsula to more than 1500 feet in Roscommon, Ogemaw and Gladwin Counties. Generally, the facies described for the Southern Peninsula are present in states to the south.

Characteristics as an Aquifer. Although detailed information regarding fluids in the Eau Claire is wanting, it is generally assumed to contain brines in the Southern Peninsula of Michigan.

Characteristics as a Confining Layer. Detailed information regarding the lithologies in the Eau Claire are unavailable, but the presence of sandstone and siltstone units suggest that it would be unsuitable for use as a confining layer.

Characteristics as an Injection Formation. The sandstone in the Eau Claire is used as an injection zone for a Ford Motor Company disposal well in Wayne County (appendix C., pl. 30).

Porosity. Unknown.

Permeability. Unknown.

Galesville Sandstone

The Galesville Sandstone is dominantly a medium-grained, silica-cemented sandstone that is locally glauconitic in the upper 10 feet. Siltstone and shaly units are present in some areas, and in Jackson County the middle zone contains a silty micaceous shale. Information regarding the details of this unit are generally wanting, but available information indicates that it attains a maximum thickness of 180 feet in Berrien County.

Franconia Formation

The Franconia includes a wide array of glauconitic dolomitic sandstone, shale, and sandy dolomite. According to Catacosinos (1973), it is not possible to distinguish the Franconia in areas where the Galesville Sandstone is not present. The maximum known thickness of the Franconia Formation is 95 feet in Ottawa County (Catacosinos, 1973).

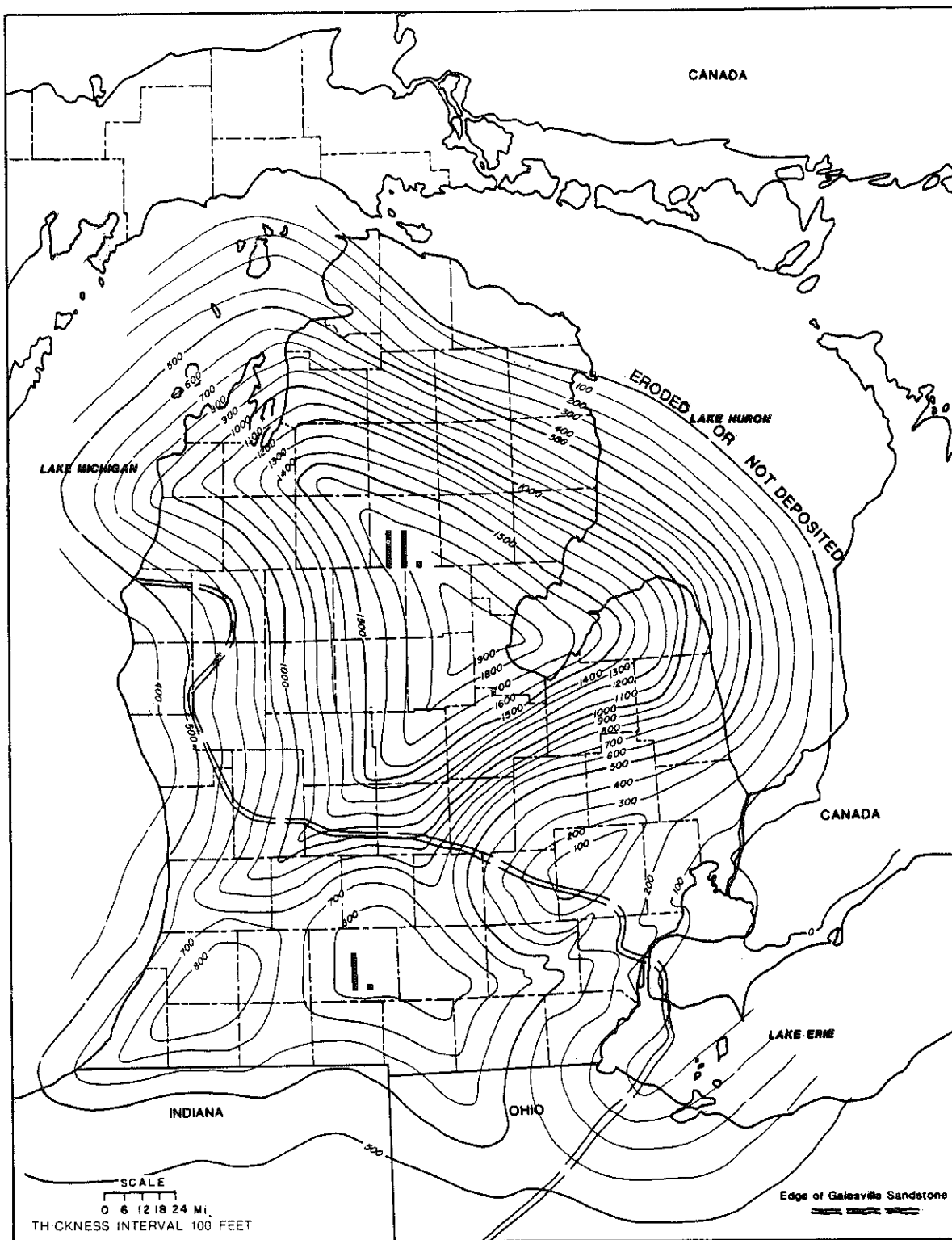


Figure 2.10. Thickness of Munising Group. I. Eau Claire, Galesville, Franconia differentiated. II. Munising Group undifferentiated, Galesville absent. (Adpated from Catacosinos, 1973.)

CAMBRO-ORDOVICIAN

In the subsurface of the Southern Peninsula, rocks that are correlative or, in part correlative, with the Au Train include in ascending order: the St. Lawrence Formation, Lodi Formation, and the Jordan Sandstone (table 2.1, fig. 2.11, pl. 9). Information regarding these units is not abundant, and because of difficulties in correlating with outcrop areas in Wisconsin and the Northern Peninsula of Michigan there are some problems with nomenclature.

Because so little information is available no attempt will be made to characterize these units. It should be noted that the recent discovery of hydrocarbons (gas) in the central part of the Southern Peninsula may be in the Jordan Sandstone. This discovery has increased exploration in this part of the stratigraphic section.

St. Lawrence Formation

According to Catacosinos (1973) the name St. Lawrence Formation should be applied to those rocks in southwestern Southern Peninsula that have been referred to as the Trempealeau, and the Prairie du Chien. In Michigan the formation is predominantly a medium-dark gray, finely crystalline to dense dolomite with glauconite, chert, dark shale, and sandstone interbeds in the upper part. A transition zone of interbedded sandstone and dolomites predominates in the Upper St. Lawrence as it grades into the overlying Jordan Sandstone. Catacosinos (1973) considered the lower Au Train to be a facies of the St. Lawrence and included the dolomite beds previously assigned to the Prairie du Chien. As a result, a Cambro-Ordovician age for the formation is indicated.

Lodi Formation

The Lodi Formation is best known from studies in Wisconsin and has only been identified in three wells in the west-central part of the Southern Peninsula (Catacosinos, 1973). The formation reaches a thickness of 170 feet in this area and is a dolomitic, micaceous siltstone and shale.

Jordan Sandstone

The Jordan Sandstone in Michigan was considered by Catacosinos (1973) to be laterally equivalent to the dolomitic sandstones of the upper Au Train of the Northern Peninsula. This interpretation does not include the St. Peter Sandstone, which historically was the designation given the sandstone above the St. Lawrence. The Jordan is composed of subangular to subrounded, fine to medium quartz grains with dolomite cement at the bottom and silica cement at the top. The formation is widely distributed in the northern two-thirds of the Southern Peninsula reaching a thickness of 580 feet in the west-central part of the Southern Peninsula; however, it is absent in the southern third of the Southern Peninsula.

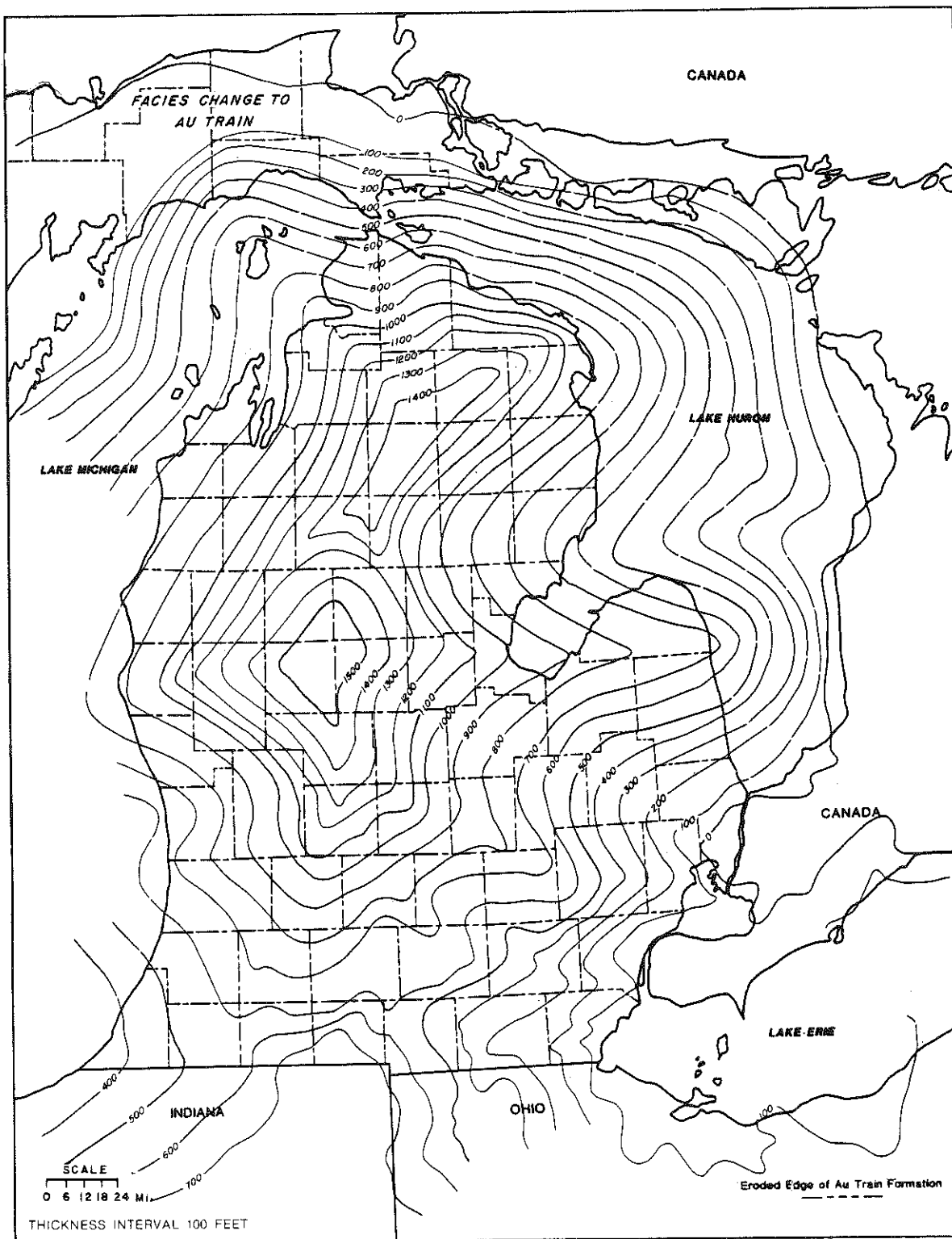


Figure 2.11. Thickness of Cambro-Ordovician St. Lawrence, Jordan, and Lodi Formations (Trempealeau-Prairie du Chien-St. Peter). (From Catacosinos, 1973.)

ORDOVICIAN

Clearly defined Ordovician rocks in Michigan include, from the oldest to youngest: the Prairie du Chien Group, the Black River Group, the Trenton Group, and the Cincinnati Series (pls. 5, 6, 8, and 10). The lower systemic boundary is placed within the Au Train Formation on outcrop, and at the base of the oolitic, cherty Oneota Dolomite in the subsurface. The Ordovician-Silurian contact is placed at the top of the interbedded shales and carbonates that comprise the Richmond Group of the Cincinnati Series. Because the basal Silurian rocks are locally an alternating sequence of limestones and carbonates the exact position of this contact is difficult to discern. The Ordovician (pl. 10) ranges in thickness from less than 800 feet in the extreme southwest portion of Michigan to greater than 1800 feet in the Saginaw Bay area and generally exceeds 1000 feet throughout the Southern Peninsula.

Prairie Du Chien Group

The Prairie du Chien Group includes part of the Au Train Formation in the outcrop area of the Northern Peninsula, and in the subsurface, in ascending order; the Oneota Dolomite, New Richmond Sandstone, and Shakopee Dolomite. The Au Train Formation comprises some 300 feet of thin to medium bedded sandy dolomite and dolomitic sandstone. It seems likely that in the subsurface the entire Prairie du Chien Group has characteristics similar to dolomite and according to Lilienthal (1978), the New Richmond is usually well-cemented by dolomite.

Characteristics as an Aquifer. The Au Train is known to produce flows of up to 250 gallons per minute from fracture and intergranular porosity. According to Sinclair (1960) solution openings in the dolomite beds may also yield water. In areas where the Au Train produces from fracture and solution openings it is especially vulnerable to contamination from surface sources of contamination.

Characteristics as a Confining Layer. The Au Train is far too permeable to function as a confining layer.

Characteristics as an Injection Formation. The Au Train is an aquifer and should not be used as an injection formation.

Porosity. Porosity in the Au Train includes void space formed by solution, fractures, and initial intergranular porosity which may have been increased by post-depositional solution.

Permeability. The unit is especially permeable in the outcrop area and immediately downdip from it. In this area, fractures and solutionally enlarged openings are greatest and interconnected porosity is widespread.

Oil and Gas Potential. The Au Train is not generally considered to be a target for hydrocarbon exploration, but correlative rocks in the subsurface of the Southern Peninsula may contain hydrocarbon accumulations. Recently (1981), a significant discovery was made in Missaukee County in rocks assigned to the St. Peter Sandstone (Jordan Formation) by the operator. This discovery has set off a flurry of exploration activity that will cause numerous wells to be drilled into these rocks, and may result in significant new reserves being found in rocks that may be a part of the Prairie du Chien Group.

Chazyan

The Prairie du Chien Group is overlain with regional angular disconformity by rocks of the Lower, Middle Ordovician Chazy Group which in Michigan consists of sandstone and the Glenwood Shale.

Glenwood Shale

The Glenwood Shale is composed of dolomitic sandstone, sandy and silty dolomite, and dolomitic shale in the western part of the Basin. The sandy and silty dolomite thins to the east and is a greenish-gray shale in central Michigan (Lilienthal, 1978). The Glenwood Shale is persistent throughout the Basin but rarely exceeds 20 feet in thickness. In Kalamazoo County, it consists of nineteen feet of shale, 18-26 feet of shale in Ottawa County, 5 feet of shale in Wayne County, and 34 feet of limestone in Muskegon County.

Characteristics as an Aquifer. None.

Characteristics as a Confining Layer. The Glenwood Shale has characteristics that suggest that it could serve as a confining layer. It is thought to be a barrier to the movement of hydrocarbons from the Black River Group into the underlying Prairie du Chien and Cambrian units.

Characteristics as an Injection Formation. The Glenwood Shale is too impermeable and thin to act as an injection formation.

Porosity. The effective porosity of the Glenwood Shale is very low.

Permeability. Very low.

Oil and Gas Potential. The Glenwood Shale is not generally regarded as being prospective for hydrocarbons.

Black River Group

The Black River Group is generally undivided in Michigan. It comprises a thick (150 to 500 feet) sequence of dense, brown to gray, micritic limestones. The group includes widespread cherty zones, and near the top encloses a thin, altered volcanic ash or metabentonite known as the "Black River Shale". The Black River Shale is a thin, distinctive bed that occurs generally south of a line interpreted to extend from Gladwin County to Kent County (fig. 2.12). The shale is generally less than 10 feet thick. In Kalamazoo County it is 4 feet of shaly limestone, becomes dominantly a limestone in Ottawa and Muskegon Counties with only a trace of shale, and is absent in Wayne and Monroe Counties.

Characteristics as an Aquifer. In the outcrop area limestones of the Black River Group produce water from solutionally enlarged bedding planes and joints. Away from the outcrop area the Black River is quite impermeable except where it has been dolomitized.

Characteristics as a Confining Layer. Although the dense limestones of the Black River are relatively impermeable to essentially impermeable, the possible presence of fractures and dolomitized zones precludes consideration of this unit as a confining layer.

Characteristics as an Injection Formation. The limestones of the Black River Group are far too impermeable to permit its use as an injection formation. In areas where the limestones have been altered to dolomite, however, it could be used as an injection formation.

Porosity. The limestones of the Black River are dense and essentially nonporous, except where they have been altered to dolomite or where bedding planes and fractures have been enlarged by solution.

Permeability. Rocks of the Black River Group are mostly dense limestones with very low permeability. Permeability has been enhanced by secondary dolomitization, fracturing and solution enlargement of bedding planes and joints. Locally, as in the Albion-Scipio oil fields and Howell fields, fracturing and secondary dolomitization have resulted in very permeable zones in this unit.

Trenton Group

Although the Trenton Group has been subdivided in the outcrop area of New York and the Northern Peninsula of Michigan, in aquifer studies and in the subsurface of the Michigan Basin it is generally regarded as a single unit. The Trenton Group consists of some 200 to more than 475 feet of light-brown to brown, fossiliferous limestone and ranges in depth from less than 1000 feet below sea level in southwest Michigan to greater than 9000 feet in an area west of Saginaw Bay (fig. 2.13). Along the southern margin of the Southern Peninsula of Michigan the upper 20 to 40 feet of the Trenton has been dolomitized, and along the Albion-Scipio trend, the Howell anticline, the Deerfield structure and in southeastern Michigan the entire Trenton-Black River section has been secondarily dolomitized.

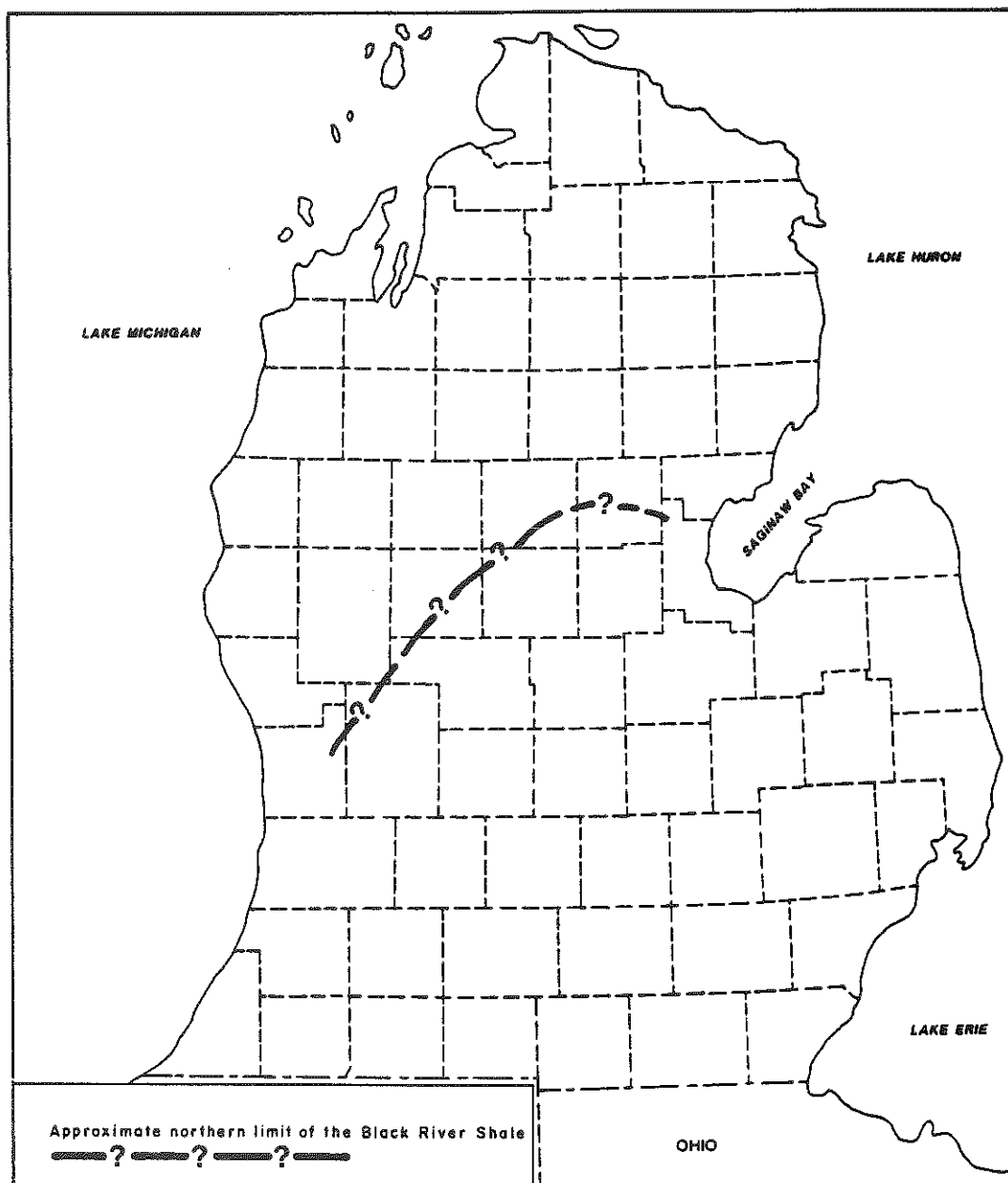


Figure 2.12. Approximate northern limit of the Black River Shale in the Southern Peninsula of Michigan.

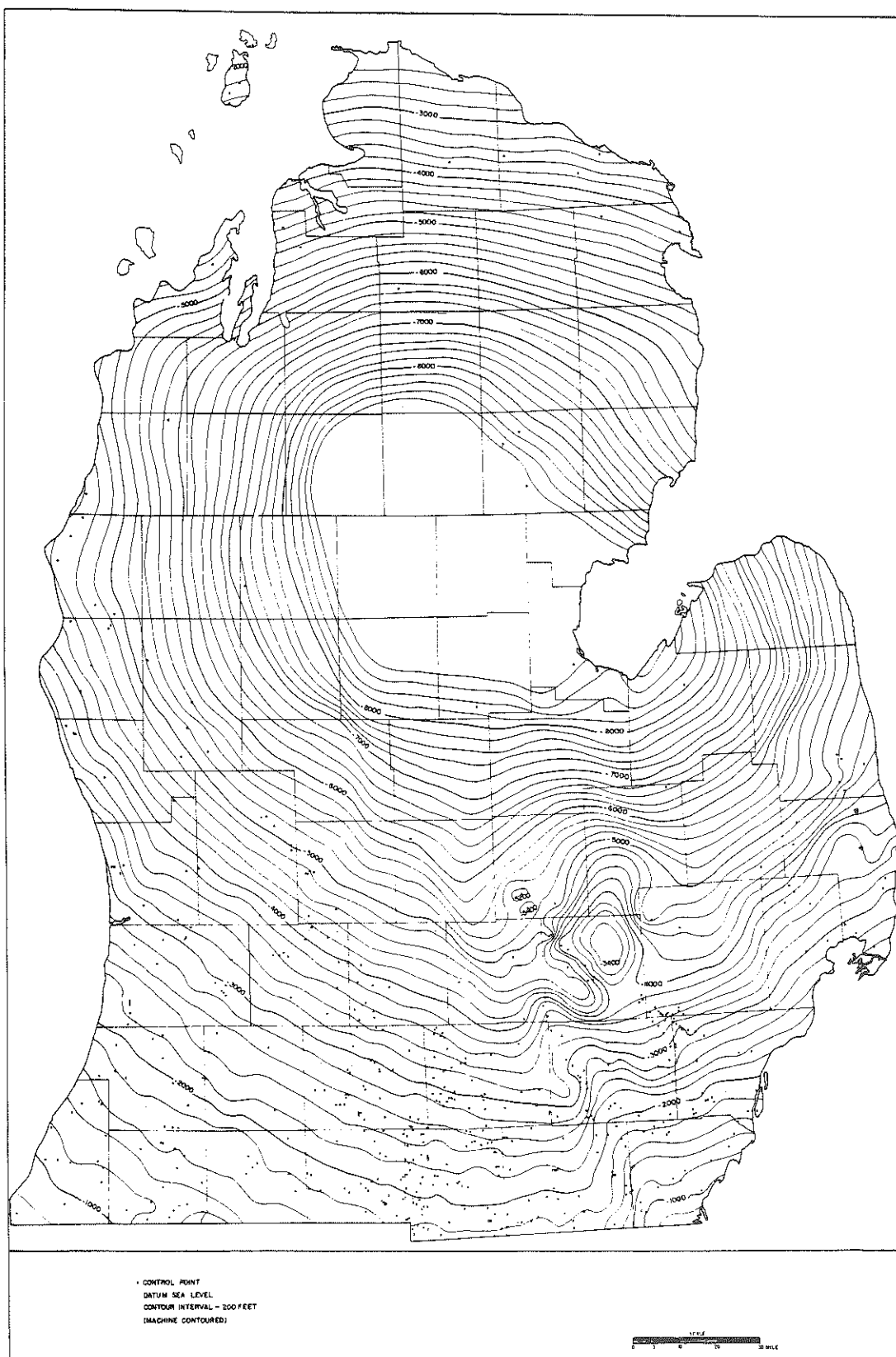


Figure 2.13. Structure contour map on top of Ordovician Trenton Group, Southern Peninsula of Michigan. (From Hinzi and Merritt in Stonehouse, 1969.)

Characteristics as an Aquifer. In and near the outcrop area, the Trenton produces water from solutionally enlarged bedding planes and joints. In the subsurface, remote from the outcrop area, the unit is generally dense and does not yield fluids except where it has been secondarily dolomitized.

Characteristics as a Confining Layer. Although the Trenton limestones are relatively impermeable, the possible presence of fractures and dolomitized zones should preclude its use as a confining layer. In the Northern Peninsula, the Collingwood Shale, an aquiclude, overlies the Trenton and separates it from the Richmond aquifer (Vanlier, 1959). It would probably protect the overlying Richmond and Silurian aquifers, but the fractured nature of the underlying Ordovician aquifers would be susceptible to updip fluid migration and thus should not be used for waste disposal even where saline. Also the underlying Black River and Trenton limestones may have sufficient artesian head to produce flowing wells.

Principle porosity zones in the Ordovician of the Southern Peninsula are along dolomitized fractures. Although sufficient thicknesses of shale exist in the Ordovician section as aquicludes, waste injection along fractures would be risky and possibly adversely affect potential hydrocarbon production. Potential for oil and gas production in an area considered for waste injection should be thoroughly investigated. Thus, the Ordovician limestones may serve as confining strata where secondary porosity has not developed.

Porosity. Extremely low except where dolomitized.

Permeability. Very low, to essentially impermeable where it has been secondarily dolomitized. Fracturing and secondary dolomitization have produced very permeable zones in the Trenton in the Albion-Scipio oil fields, and on the Howell anticline.

Oil and Gas Potential. The Trenton is an important exploration target in the Michigan Basin. The Ordovician Trenton-Black River has produced oil in the Michigan Basin since 1935 and gas since 1954 from 20 fields in 9 counties of southcentral and southeast Michigan (Michigan Geological Survey, 1979).

Utica Shale

The Utica is a hard, dark gray to greenish-black, calcareous shale that is fairly homogeneous throughout. In Michigan, the contact between the Utica and the underlying Trenton is abrupt and distinctive. The contact with the overlying Cincinnati Series is gradational and marked by an increase in limestone. The Utica is persistent across the Basin. It is more than 400 feet thick in southeastern Michigan and about 200 feet thick in the outcrop area of the Northern Peninsula (pl. 10).

Characteristics as an Aquifer. The Utica is not an aquifer.

Characteristics as a Confining Layer. The very low permeability of this rather thick shale coupled with the fact that it forms the seal on known hydrocarbon traps indicates that it is an excellent confining layer.

Characteristics as an Injection Formation. The Utica is far too impermeable for use as an injection formation.

Porosity. The effective porosity of the Utica Shale is very low. Briggs (1963) reported 1.5 to 4.2 percent from cores taken in the Consumers Power Company Brine Disposal Well No. 139, Sec. 39, T. 4N., R. 15E.

Permeability. Permeabilities of less than 0.5 to 2.5 md were reported by Briggs (1963).

Oil and Gas Potential. None.

Cincinnatian Series

Although the Cincinnatian Series in the type area includes lithologies equivalent to the Utica Shale, in the Michigan Basin this series name is used for that portion of the Ordovician section that lies between the Utica and the base of the Silurian. This part of the section comprises a sequence of interbedded shales and carbonates. In the outcrop area of the Northern Peninsula, these rocks have been subdivided into a number of units, but in the subsurface and in aquifer studies of the Northern Peninsula they are generally simply regarded as the Cincinnatian Series. The rocks considered to be Cincinnatian range in thickness from about 230 feet to as much as 450 feet.

Characteristics as an Aquifer. A few wells produce small amounts of water from the Cincinnatian in the outcrop area. A short distance downdip from the outcrop area, the limestones and shales that make up this unit are too impermeable to yield water to wells.

Characteristics as a Confining Layer. Away from the outcrop area the Cincinnatian Series is an excellent confining layer.

Characteristics as an Injection Formation. The rocks of the Cincinnatian are far too impermeable to be used as an injection formation.

Porosity. In the outcrop area the carbonates of this unit have a low effective porosity.

Permeability. In and near the outcrop area the carbonates and shales that make up this unit are slowly permeable. Away from the outcrop area these lithologies are essentially impermeable.

Oil and Gas Potential. Very low.

SILURIAN

The Silurian of Michigan includes from 600 feet to more than 4000 feet of rock that has been assigned to the Lower (Alexandrian), Middle (Niagaran) and Upper (Cayugan) Silurian Series (figs. 2.14 and 2.15, pls. 5,6,8, and 10). In the outcrop area and throughout the subsurface of the Southern Peninsula all Lower Silurian rocks are assigned to the Cataract Group, a sequence of dolomite, cherty dolomite, shale, and gypsum that is 150 to 200 feet thick. Middle Silurian rocks comprise a thick sequence of carbonate (mainly dolomite) units in the eastern Northern Peninsula. In the subsurface of the Southern Peninsula, rocks in this series undergo a number of facies changes that reflect the development of a reef-rimmed basin during Middle Silurian time. Upper Silurian rocks have been designated the Salina Group in the eastern Northern Peninsula and the Salina and Bass Islands Groups in southeastern Michigan.

LOWER SILURIAN

Cataract Group

Rocks of the Cataract Group have not been extensively studied. In the subsurface, the base of the unit is difficult to pick as the carbonate rocks interbedded with shale closely resemble lithologies in the upper part of the Richmond Group (Ordovician). In the southern Southern Peninsula the upper boundary of the Cataract Group is generally picked at the base of the Clinton Shale. In the central and northern Southern Peninsula where the Clinton Shale is missing, the top of the Cataract is considered to be the first chert zone in the thick sequence of carbonates known as the "Niagaran". At the outcrop area on the Northern Peninsula the Cataract Group is equivalent to the Manitoulin Dolomite, Cabot Head Shale, and the Moss Lake Formation.

Characteristics as an Aquifer. Rocks of the Cataract Group are not generally considered to be aquifers. In the eastern Northern Peninsula where these rocks are at the surface and have been leached of gypsum by meteoric waters some potable water is produced, but it is generally very hard and too mineralized for most uses.

Characteristics as a Confining Layer. The shales and gypsum beds in the Cataract Group should give it a low permeability and cause annealing of fractures such that it would perform well as an aquiclude.

Characteristics as an Injection Formation. Generally unsuitable.

Porosity. Void spaces have formed by the dissolution of gypsum in outcrop area, but elsewhere porosity is very low.

Permeability. Pore spaces are generally poorly connected and permeability is very slow except locally where there has been dissolution of gypsum layers.

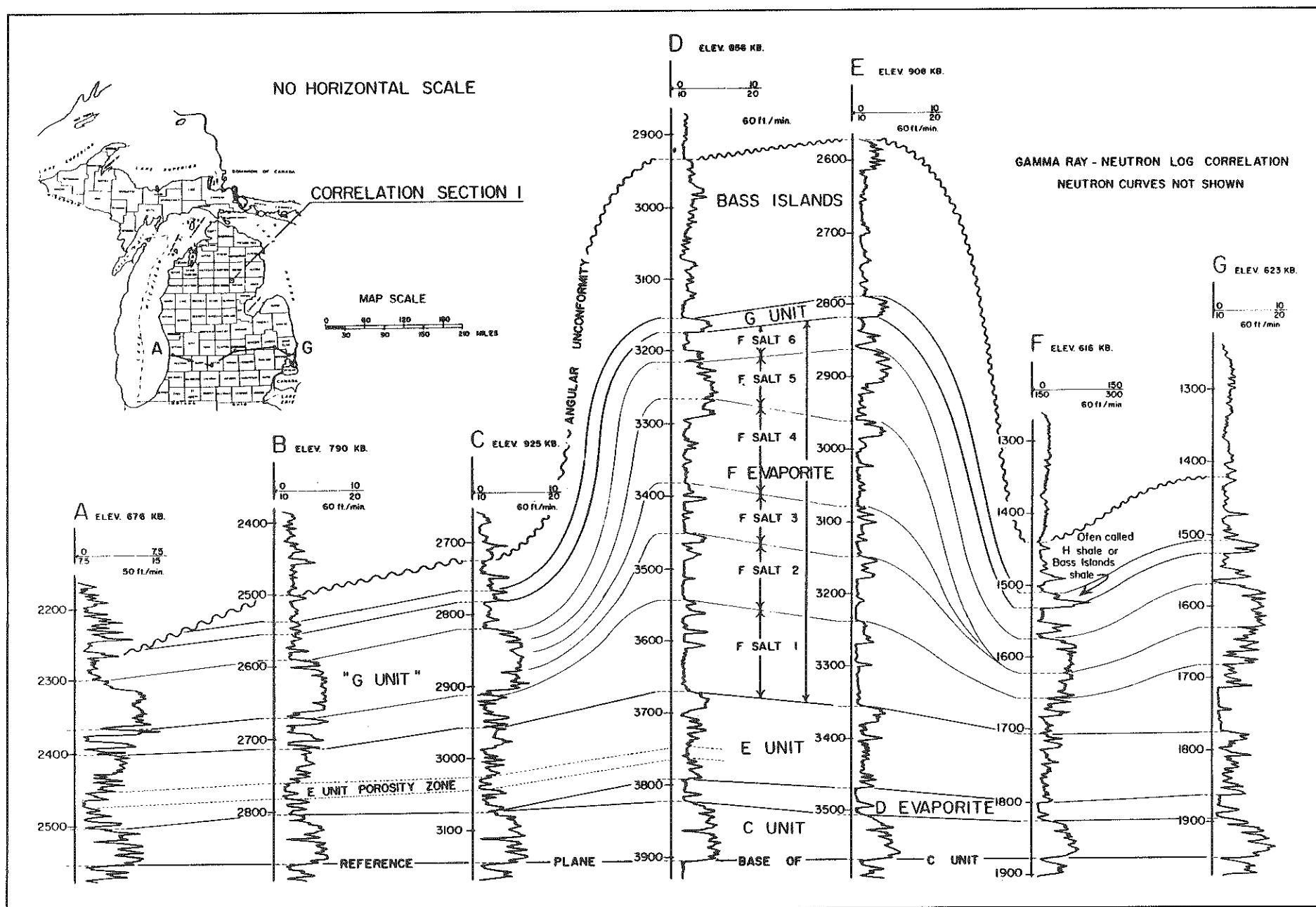
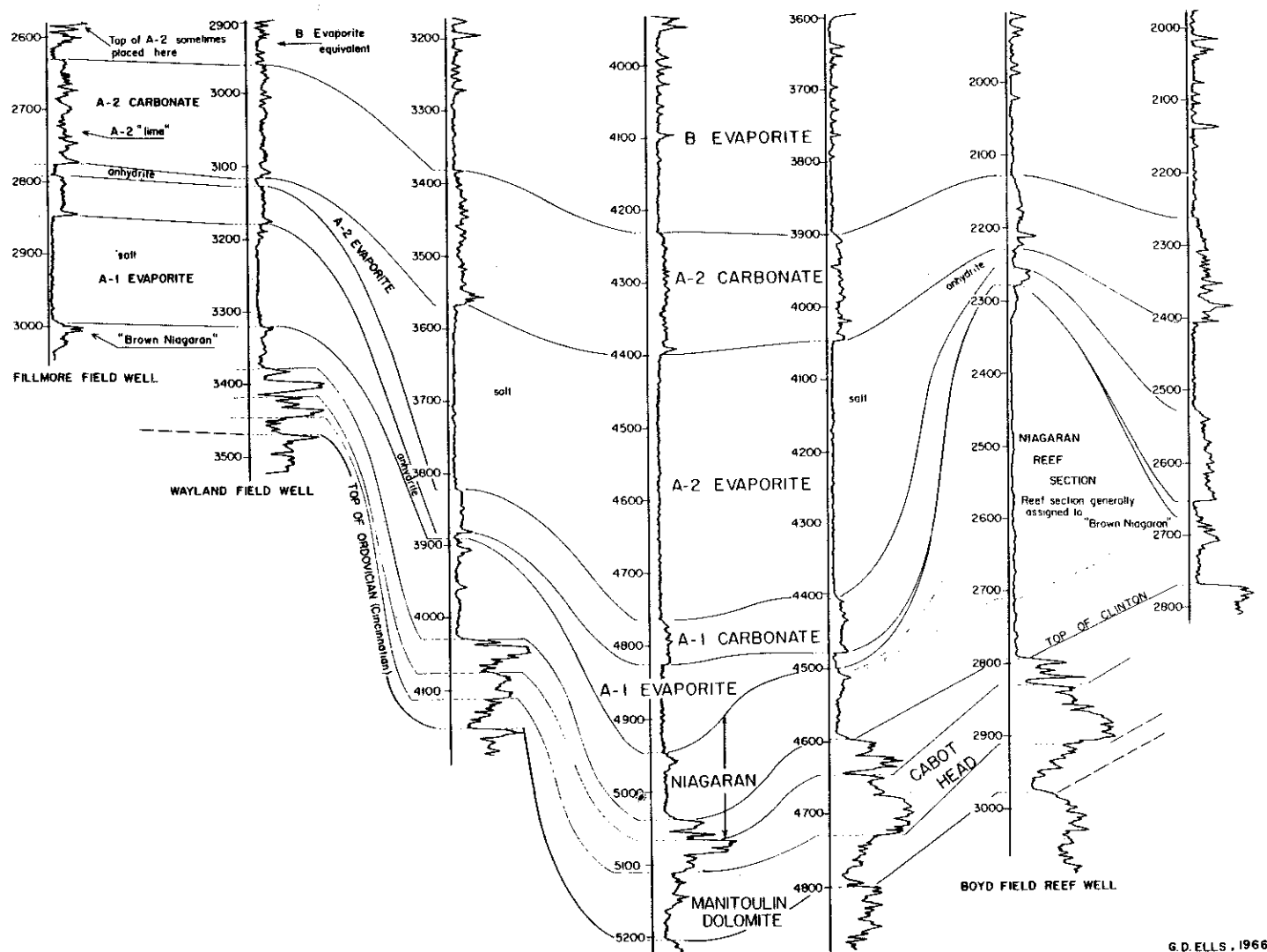


Figure 2.14. Subsurface Silurian correlations across southern Michigan, Ottawa County to St. Clair County.
(From Ellis, 1978.)



WELL LOCATIONS

- A** Well Permit 21724
Humble Oil & Refining Company, Adler-Schoep Comm. No. 1
Section 34, T.5N, R.15W., OTTAWA COUNTY
Schlumberger GR-N Log
- B** Well Permit 21613
Michigan Consolidated Gas Company, G. Fales No. 1
Section 17, T.3N, R.11W., ALLEGAN COUNTY
Schlumberger GR-N Log
- C** Well Permit 22672
The Petroka Corporation, Chas & Lamonte No. 1
Section 18, T.2N, R.5W., EATON COUNTY
Schlumberger GR-N Log
- D** Well Permit 22379
C. A. Lee, Ferris No. 1
Section 5, T.5N, R.2E., SHIAWASSEE COUNTY
Schlumberger GR-N Log
- E** Well Permit 22534
Sunray Mid-Continent Oil Company, Richardson No. 1
Section 18, T.6N, R.12E., LAPEER COUNTY
Schlumberger GR-N-L Log
- F** Well Permit BD 139
Consumers Power Company, C.P.C. BD No. 1
Section 31, T.4N, T.15E., ST. CLAIR COUNTY
Schlumberger GR-N-L Log
- G** Well Permit 23199
R.W. Davine, Sullivan & Leroux, Mano-Newman Unit No. 1
Section 30, T.5N, R.17E., ST. CLAIR COUNTY
Schlumberger GR-N Log

Fig. 15. Correlation Section 2, west to east cross section. (From Ellis et al., 1979.)

Special Considerations. Wells penetrating fresh water aquifers above the Cataract should not be drilled into these rocks without special care. Formation waters from them may invade and contaminate near surface aquifers bearing potable water.

Oil and Gas Potential. The Cataract Group is not generally regarded as a target for oil and gas exploration.

MIDDLE SILURIAN

Rocks commonly assigned to the Middle Silurian (Niagaran Series) include a basal shale (Clinton Shale) in southern Michigan and a complex of carbonate rocks known as the Niagara Group in the Southern Peninsula in the outcrop area of the eastern Northern Peninsula.

Outcrop Area

In the outcrop area, rocks of Middle Silurian age form the Burnt Bluff Group (Lime Island Dolomite, Bryon Dolomite and Hendricks Dolomite), the Manistique Group (Schoolcraft Dolomite and Cordell Dolomite) and the Engadine Dolomite. These units comprise some 500 feet of dolomite that is the most important source of fresh water throughout much of their outcrop area. Springs, karst features and flowing artesian wells are the result of dissolution along bedding planes and fractures.

Characteristics as an Aquifer. No detailed production data have been reported for wells in these rocks, though they are the most important aquifer at the area of their outcrop. Available information indicated that small to large supplies of water can be obtained from these rocks depending mainly on the size and number of permeable zones intersected by the well bore.

Characteristics as a Confining Layer. Although thick, relatively impermeable layers in these units may serve to confine artesian systems, it is unlikely that the units are free of fractures over large areas. Enlarged joints and bedding planes are known to extend over considerable areas which should preclude use of these units as confining layers.

Porosity. Cavernous porosity has been produced by solutional enlargement of joints and bedding planes.

Permeability. The cavernous zones in these rocks act as large conduits for the movement of water. Away from the cavernous zones, beds within these units are very slowly permeable to impermeable.

Oil and Gas Potential. In both the outcrop area and in the sub-surface downdip on the Northern Peninsula the potential for oil and gas accumulations in these rocks is very low.

Subsurface

In the subsurface of the Southern Peninsula of Michigan rocks of the Middle Silurian Niagara Group form gradational zones with distinctive rock characteristics. In the central part of the basin, the Niagara Group consists of a thin (50-120 feet) dense limestone (micrite) termed the basinal facies that grades outward into a dolomitic limestone. It then grades into a porous dolomite (fig. 2.16) termed the shelf facies (Burgess and Benson, 1969) and ranges in thickness from about 120 to 300 feet. The shelf facies is characterized by the presence of locally thick areas in the form of "pinnacle" reefs (fig. 2.17). Outward this facies grades into a thick (300 feet to 500 feet) zone (Mesolella and others, 1974) called the bank facies. This zone is composed of porous and permeable dolomite and extends southward into Indiana and Ohio and northward into the outcrop area.

Basinal Facies

The basin facies of the Niagara Group is a thin, dense, fine-grained limestone that is probably time equivalent to only the lower portion of the bank facies. The basin facies is separated from the overlying Salina evaporite sequence by only a thin limestone. In the central portion of the basin downward percolating waters have transported salt into openings in the dense limestone of the Niagara Group and have essentially "salt-plugged" all void space.

Characteristics as an Aquifer. The Basin facies of the Niagara Group is not an aquifer. Any water in this unit would contain sodium chloride to the saturation point (more than 300,000 parts per million).

Characteristics as a Confining Layer. Because the void space in this unit is essentially all plugged with secondary salt deposits it should be an excellent confining layer.

Characteristics as an Injection Formation. The Basinal facies of the Niagaran is generally too impermeable to be used as an injection formation.

Porosity. Extremely low. Dense micrite is very slowly permeable. Secondary precipitation of salt in the available void space has reduced the porosity to essentially zero.

Permeability. Extremely low.

Oil and Gas Potential. This facies of the Niagaran is not generally considered to be an exploration target for oil and gas.

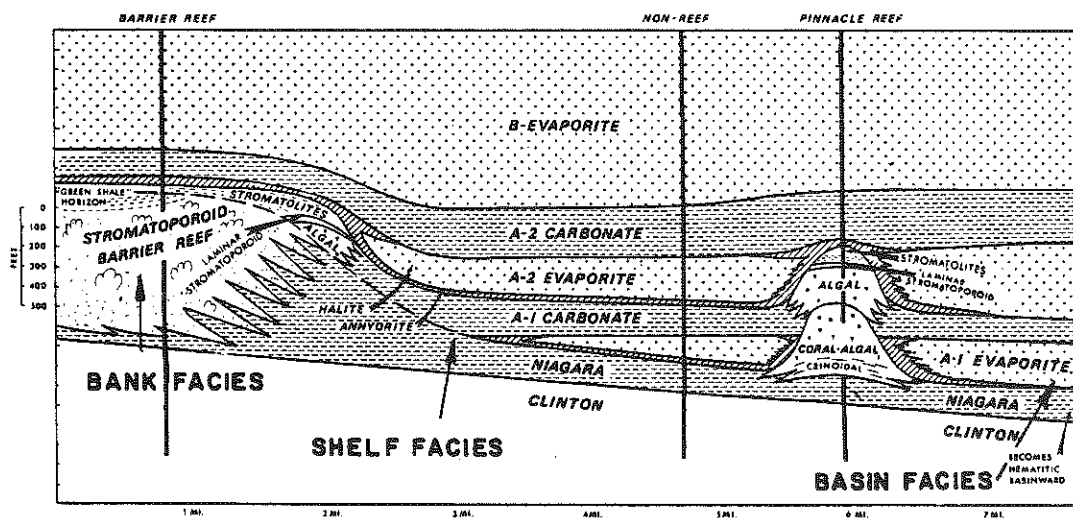


Figure 2.16. Generalized cross section of Niagara and lower Salina carbonates and evaporites, northern Michigan basin. (Modified from Mesolella, 1974.)

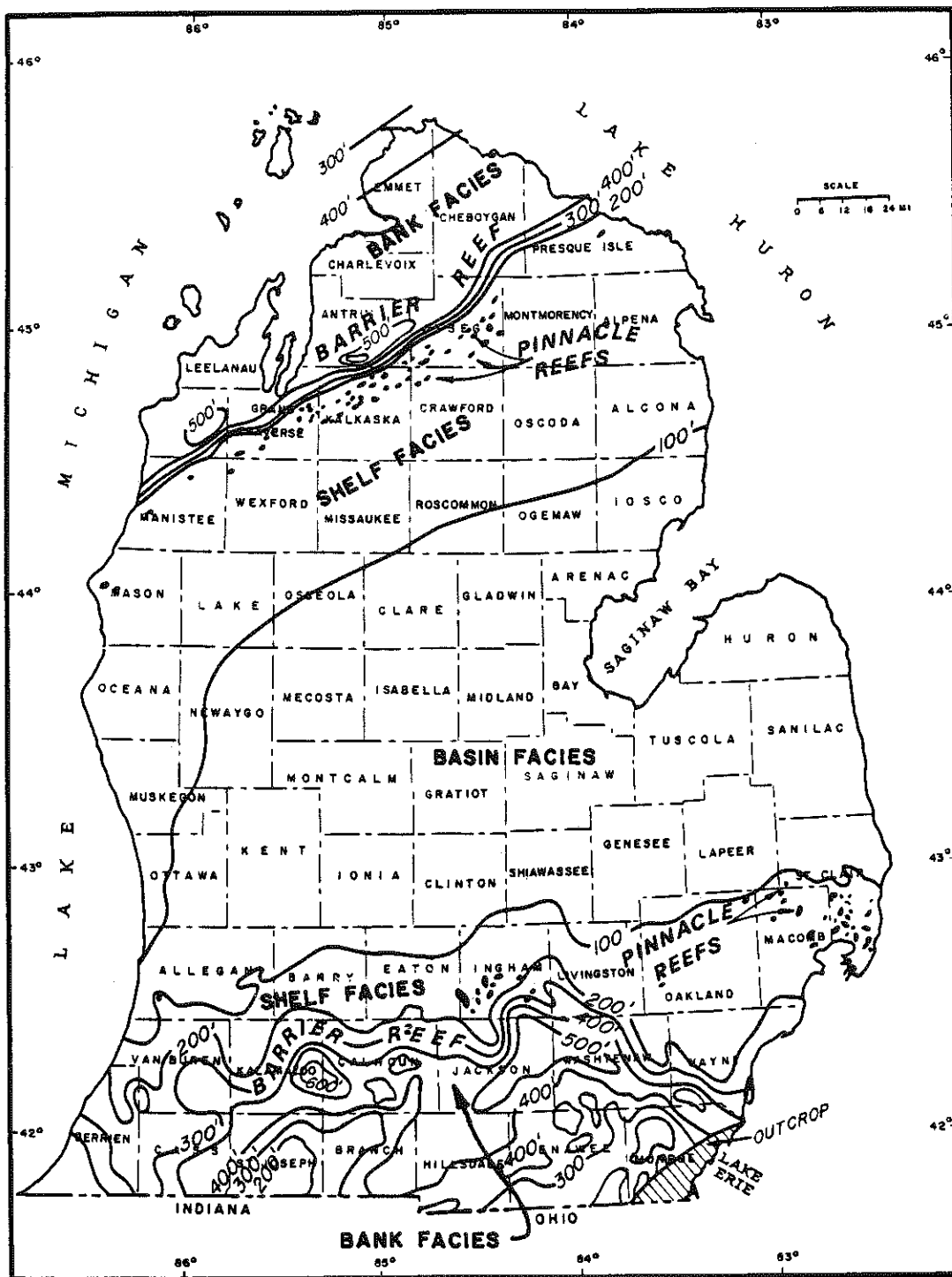


Figure 2.17. Thickness and facies of the Niagara Group.
(From Mesolella, 1974.)

Shelf Facies

The shelf facies of the Niagaran, a dolomitized skeletal limestone, encircles the basin facies and grades outward into the bank facies (fig. 2.17). The shelf facies thickens outward from about 100 feet on its inner margin to 300 feet and includes local thick areas known as "pinnacle" reefs. The reefs range up to 1200 acres in areal extent and in many areas are productive of oil and gas. The shelf facies is relatively impermeable near its junction with the basin facies, but as the unit thickens outward it undergoes a concomitant increase in porosity. The reefal areas are typically very porous and permeable. Many of these features contain gas, oil and brine, although a few are known that contain only brine.

Characteristics as an Aquifer. Near the basin/shelf facies transition, this unit has very low porosity. The facies thickens outward toward the bank facies and thickening is accompanied by more complete dolomitization. Porosity and permeability increase with dolomitization.

Characteristics as a Confining Layer. Throughout most of its extent this unit is too permeable to serve as an aquiclude. The presence of randomly located very permeable reefal buildups that may be exploited for oil and/or gas further argue against its use as a confining layer.

Characteristics as an Injection Formation. Near the shelf/bank facies transition and in reefal buildups the bank facies is generally very porous and permeable. It is used for gas storage (pl. 31) and would readily accept a wide range of fluids. In Michigan, fluids in this unit include oil, gas and brine. The presence of recoverable hydrocarbons in this unit would seem to preclude its use as an injection formation.

Porosity. The process of dolomitization has greatly increased the porosity in this unit. Consequently the unit is least porous in the transition zone with the dense limestone of the basin facies and most permeable in reefal buildups and adjacent to the bank facies.

Permeability. The lithologies that make this unit permeable also contribute to porosity; that is, increased porosities yield increased permeabilities. Thus the shelf facies is least permeable along its basinward margin and most permeable adjacent to the bank facies.

Oil and Gas Potential. The shelf facies of the Middle Silurian Niagara Group has produced large quantities of oil and gas, particularly from the pinnacle reefs. The Niagaran has produced oil in Michigan since 1952 and gas since 1929 (Mich. Geol. Survey, 1979) from over 500 fields in 25 counties (fig. 2.18). This includes over 350 fields in the northern reef trend.

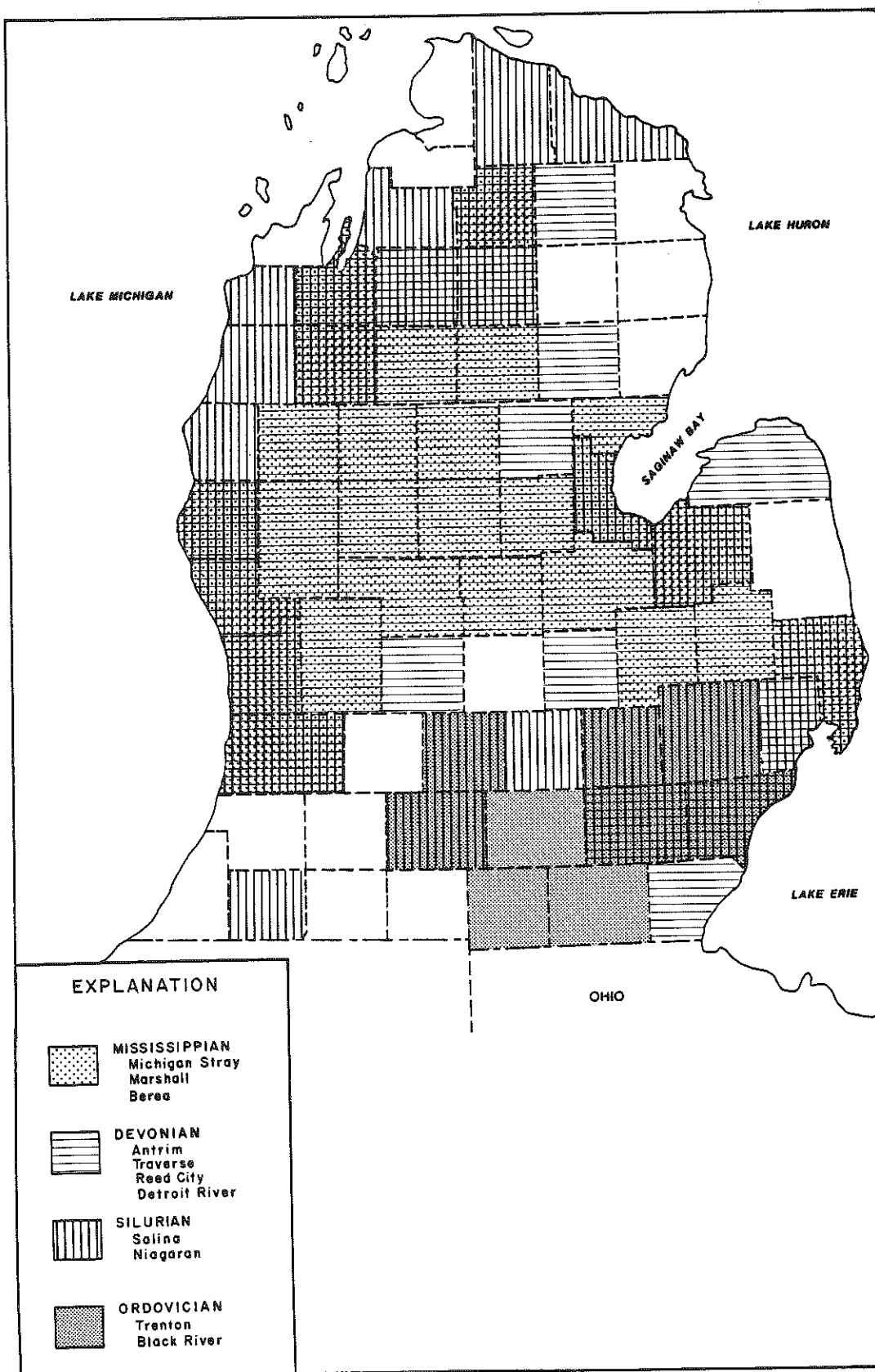


Figure 2.18. Oil and gas production in Michigan by county and geologic age. (From Michigan Geological Survey, 1979.)

Bank Facies

The Niagaran section is thickest in the bank facies of the Upper Peninsula where it is as much as 900 feet thick. Across the southern Lower Peninsula the facies is between 300 feet and 400 feet thick. The Bank facies is a dolomitized carbonate bank-reef complex that developed along and on the stable arch areas (Findly Arch, Algonquin Arch, Wisconsin Arch, and Indiana Platform). Here, the Michigan Basin subsided less and widespread organic activity resulted in a broad accumulation of reefal material. Dolomitization of this unit has produced a very porous and permeable lithology that is generally filled with brine throughout the subsurface. In the outcrop area of the Upper Peninsula, the bank facies (Burnt Bluff Group, Cordell Group and the Manistique Dolomite) has been flushed of brine and contains fresh water.

Characteristics as an Aquifer. The bank facies is an aquifer in the Upper Peninsula. In the subsurface, although the unit is very porous and permeable, it contains brines rendering it unsuitable as an aquifer.

Characteristics as a Confining Layer. The bank facies is far too permeable to be a confining layer.

Characteristics as an Injection Formation. Although the very high porosity and very rapid permeability of the bank facies of the Niagaran would seem to make it an ideal injection formation, the fact that it has been, and no doubt will be, penetrated by numerous tests for oil and gas greatly diminishes its availability for waste disposal other than brine.

Porosity. Locally very porous. On outcrop this facies contains cavernous porosity; in the subsurface of the southern Lower Peninsula it displays vuggy and moldic (leached) porosity.

Permeability. On outcrop permeability is associated with cavernous zones. In the subsurface of the southern Lower Peninsula the unit is generally permeable throughout.

Oil and Gas Potential. The bank facies of the Niagaran does not produce oil or gas and hydrocarbon shows in this unit are uncommon. Thus its potential for oil and gas production is considered low.

Salina Group

In the Michigan Basin subsurface the Upper Silurian is represented by the Salina and Bass Islands Groups. The Salina Group is a thick sequence of carbonate, anhydrite, salt and shale. A number of these lithologies are restricted to an area roughly equivalent to the combined extent of the basin and shelf facies of the Niagaran Group.

The basal portion of the Salina was designated the "A" member by Landes (1945). The "A" was further subdivided by Evans (1950) into a basal unit he termed the A-1 and an upper unit he named the A-2. Each of these units consists of a lower evaporite unit and upper carbonate. Each of the four "A" elements are extensive enough to warrant formational status, and at least the A-1 Carbonate has been elevated to this rank (Budros, 1974).

Characteristics as an Aquifer. The Salina serves as an aquifer only in its outcrop area in southeastern Michigan and the eastern part of the Northern Peninsula, especially on the St. Ignace Peninsula, where it produces from joints and bedding planes in dolomite.

Characteristics as a Confining Layer. Throughout the central portion of the Michigan Basin where the group contains thick salts and basinward of the reef trend, the unit is essentially an aquiclude.

Characteristics as an Injection Formation. Solution and fracture permeability, variable lithology, and aquifer and hydrocarbon reservoir potential render the Salina Group generally unfavorable as an injection unit. However the Salina is utilized for brine injection in St. Clair County.

Porosity. Porosity associated with joints, brecciation fractures and solution along bedding planes is common in the Northern Peninsula.

Permeability. Highly variable fracture and bedding plane permeability in Northern Peninsula.

Oil and Gas Potential. Near the margins of the evaporite containing Salina, the A-1 and A-2 Carbonates produce hydrocarbons.

A-1 Evaporite

The A-1 Evaporite consists of a basal and upper anhydrite that enclose a thick salt in the basinal area (fig. 2.19, pl. 10). The salt consists mainly of halite (NaCl), but it contains up to 40 feet of sylvite (KCl) in the center of the basin (Matthews, 1970). The unit is anhydrite over most of the Niagaran shelf facies. It is generally not present south of the shelf facies and extends only a short distance onto the bank facies in the northern Lower Peninsula (fig. 2.17 and 2.19). Locally, as long a line from Holland, Michigan southeast to Wayland and beyond, the A-1 salt has been removed by dissolution and the overlying rock has been draped over the abrupt escarpment formed by the salt.

Characteristics as an Aquifer. The A-1 Evaporite is not an aquifer.

Characteristics as a Confining Layer. The anhydrite beds and salt of the A-1 Evaporite are essentially impermeable and are excellent confining layers. Furthermore, they contain only a very small amount of formation water, and fractures in either lithology should "heal" either by flowage or secondary mineral growth.

Characteristics as an Injection Formation. None.

Porosity. Extremely low.

Permeability. Essentially impermeable.

Oil and Gas Potential. The A-1 Salt contains gas over some major structures. Gas was tested from this zone over the Mio anticline in Ogemaw County and over the Kawkawlin anticline in Bay County.

A-1 Carbonate

The A-1 Carbonate overlies that portion of the Michigan Basin underlain by the basin and shelf facies of the Niagaran Group and extends northward some distance onto the northern portion of the bank facies (fig. 2.20). South of the shelf facies in the southern part of the Southern Peninsula, the A-1 Carbonate extends only a short distance onto the bank facies. The carbonates in the A-1 are generally limestone except in areas adjacent to reefal buildups, over the abrupt margin of the A-1 salt in southwestern Michigan, and in local areas along its distal margins.

The A-1 Evaporite is gradational upward into the basal A-1 Carbonate and the A-1 Carbonate is apparently gradational into the overlying A-2 Evaporite. In areas where the A-1 Carbonate is overlain by the A-2 salt and underlain by the A-1 salt, all porosity in it is plugged by salt (halite). The A-1 Carbonate is less than 60' thick in the central part of the Michigan Basin and is more than 150 feet thick where it overlies the carbonate bank facies in the northern Lower Peninsula.

Characteristics as an Aquifer. The A-1 Carbonate is not an aquifer.

Characteristics as a Confining Layer. In areas where the A-1 Carbonate is limestone and salt plugged, it is an excellent confining layer.

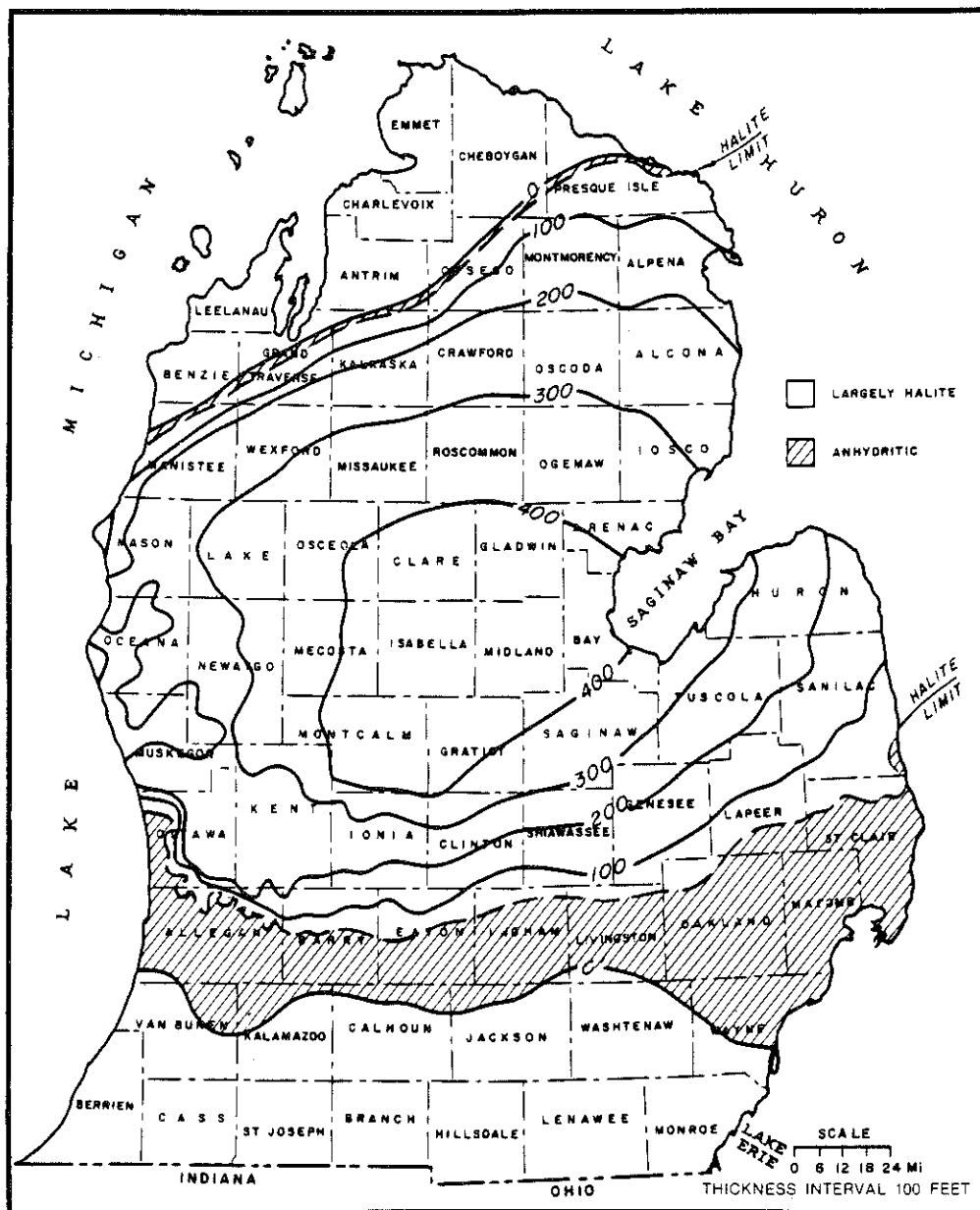


Figure 2.19. Thickness of the A-1 evaporite. Contour interval is 100 feet. (From Mesolella, 1974.)

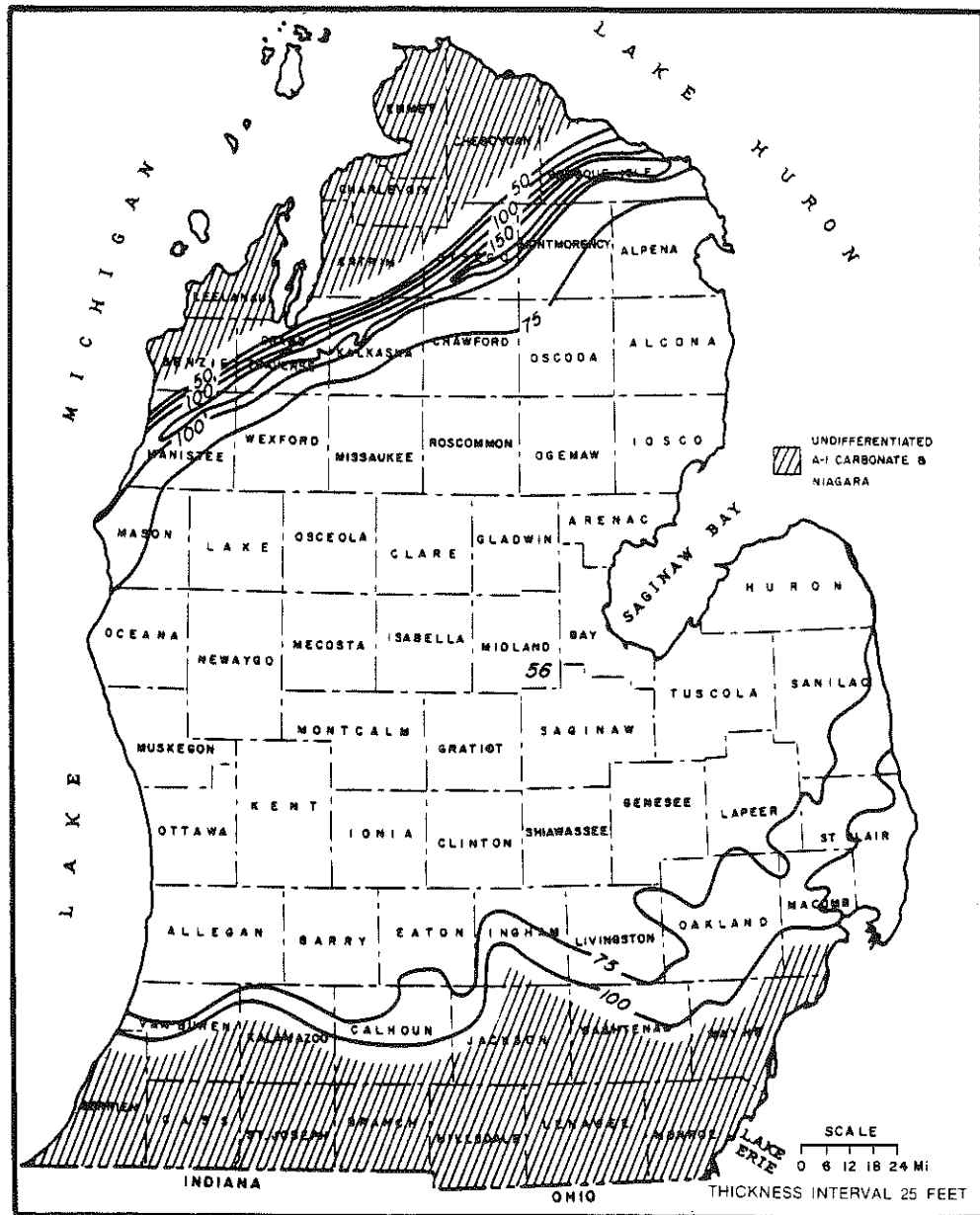


Figure 2.20. Thickness of the A-1 Carbonate. Contour interval is 25 feet. (From Mesolella, 1974.)

Characteristics as an Injection Formation. The A-1 Carbonate will accept fluids only where it is dolomite. In such areas, it is a target for oil and gas exploration, is productive of hydrocarbons, or it is in contact with very permeable reefal dolomites of the Niagaran.

Porosity. In areas where this unit is dolomite, it has low porosity. In areas where it is limestone and salt-plugged, it has extremely low porosity.

Permeability. Dolomites of the A-1 Carbonate are slowly permeable, and salt-plugged limestones are essentially impermeable.

Oil and Gas Potential. The A-1 Carbonate produces hydrocarbons and is an exploration target in those areas where reefs are developed in the Niagara Group.

A-2 Evaporite

The A-2 Evaporite conformably overlies the A-1 Carbonate except over "pinnacle" reefs where it lies directly on the Niagaran (fig. 2.21). It is dominantly halite and ranges from a zero edge at the basin margin to more than 475 feet thick in the central part of the basin (Tremper, 1973). Over the bank reef complex it is a dense anhydrite generally less than 40 feet thick. A-2 salt has been removed by dissolution southwestward of a line that extends from Muskegon southeastward to the Walker Oil Field in Kent County. The A-2 salt, may have been removed in the area just north of the Straits of Mackinac and south to the present salt margin.

Characteristics as an Aquifer. The A-2 Evaporite is not an aquifer.

Characteristics as a Confining Layer. The A-2 Evaporite is an excellent confining layer. It is the seal over the pinnacle reefs that developed in the shelf facies of the Niagaran and has the properties necessary to confine fluids under pressure.

Characteristics as an Injection Formation. Unsuitable.

Porosity. Extremely low.

Permeability. Extremely low.

Oil and Gas Potential. None.

A-2 Carbonate

The A-2 Carbonate is limestone in the central part of the basin and is dolomite over the bank facies and over pinnacle reefs in the southern part of the Lower Peninsula. This unit is more than 150 feet thick in the middle of the basin and thins to less than 50 feet in the northernmost part of the Lower Peninsula (fig. 2.22). It also thins across the southern extension of the bank facies and is difficult to distinguish, or absent, in the area just north of the Michigan-Indiana State line.

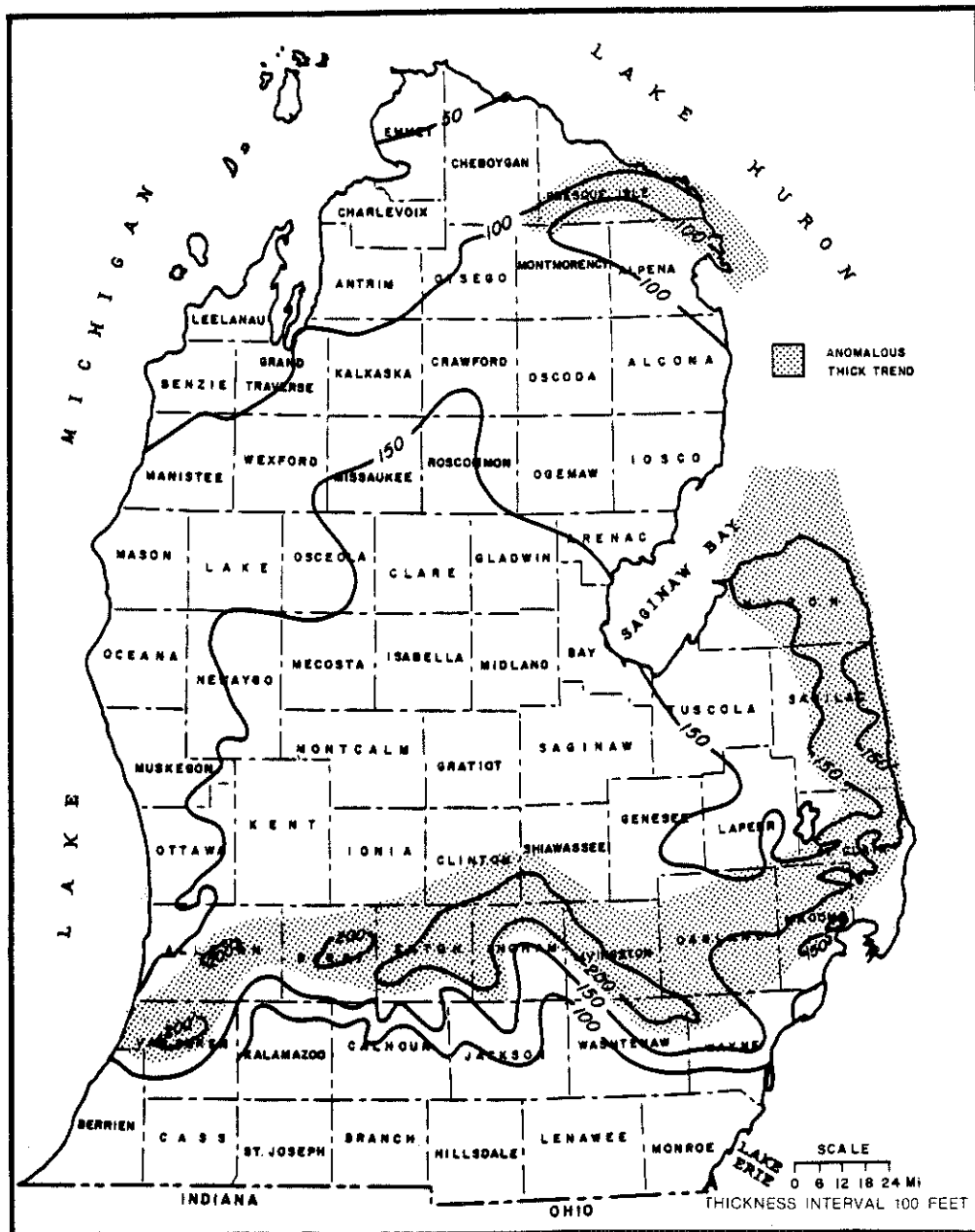


Figure 2.22. Thickness of the A-2 Carbonate. Contour interval is 50 feet. (From Mesolella, 1974.)

Characteristics as an Aquifer. The A-2 Carbonate is not an aquifer. Where the unit is a dolomite, it is slightly porous and slowly permeable, but contains oil and/or gas or brine.

Characteristics as a Confining Layer. In areas where this unit is limestone, all pore space is generally plugged with salt. In such areas it is an excellent aquiclude.

Characteristics as an Injection Formation. In areas where the A-1 Carbonate is dolomite it may serve as an injection formation, but its hydrocarbon potential should first be evaluated. It is currently used as a gas storage reservoir along the A-1 salt edge in southwestern Michigan.

Porosity. Where the A-1 Carbonate is limestone it has very little porosity. In the areas where it is dolomite, it has a porosity of a few percent.

Permeability. The A-2 Carbonate is virtually impermeable in areas where it is a limestone and is salt-plugged. Where it has undergone dolomitization, it is slowly permeable.

Oil and Gas Potential. The A-2 has produced gas in areas where it is dolomite.

B Member

The unit defined as the "B" Member by Landes (1945) includes, in the central part of the basin, up to 450 feet of basal salt and an upper unit comprised of 0 feet to about 80 feet of shale, dolomite and anhydrite (fig. 2.23). The B-salt is thickest in the basin and thins toward the northern carbonate bank where it thickens (Tremper, 1973). North of the thickest portion of the bank facies the unit thins toward the basin margin. On the southern flank of the basin, the B-salt does not extend south of the southern edge of the shelf facies of the Niagaran. The upper part of the B, termed the B-Unit by Ellis (1978) thins from a maximum of more than 80 feet in the basin center to a zero edge near the Straits of Mackinac on the north and over the northern part of the bank facies and the southern flank of the basin.

Characteristics as an Aquifer. Neither the B-salt nor the B-Unit is an aquifer.

Characteristics as a Confining Layer. The B-salt and the B-Unit are excellent confining layers. The thick salt section in the central part of the basin would be most effective, but the presence of either salt or anhydrite should indicate that the member is an aquiclude.

Characteristics as an Injection Formation. Unsuitable.

Porosity. Essentially impermeable.

Permeability. Essentially zero.

Oil and Gas Potential. Very little to none.

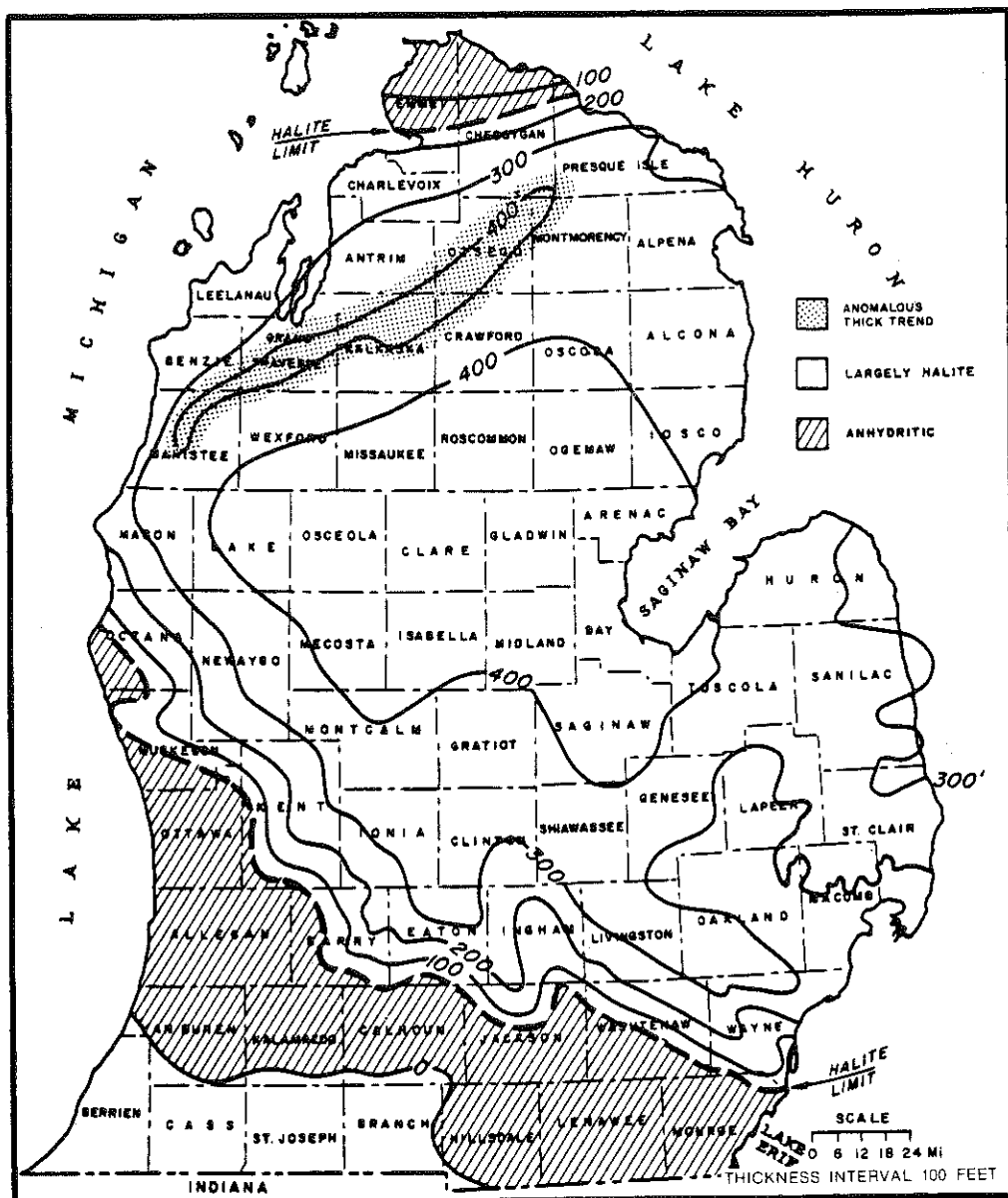


Figure 2.23. Thickness of the B Evaporite. Contour interval is 100 feet. (From Mesolella, 1974.)

C Shale

The C-Unit is a dolomitic shale with beds of anhydrite and dolomite. It is more than 115 feet thick in the central basin area, thins to 70 feet across the thick portion of the northern bank facies and is more than 100 feet thick near the Straits of Mackinac (fig. 2.24). The unit thins across the southern bank facies, becomes more carbonate rich, and according to Shaver (personal communication, 1980) grades into the Mississenawa Shale in Indiana.

Characteristics as an Aquifer. None.

Characteristics as a Confining Layer. The C-Shale is a plastic shale and should not maintain open fractures at depth. Thus, it is considered to be an excellent confining layer.

Characteristics as an Injection Formation. Unsuitable.

Porosity. Effective porosity is essentially zero. Porosity associated with clay minerals is quite high.

Permeability. Essentially impermeable.

Oil and Gas Potential. None.

D-Unit

The Salina D-Unit is composed of two salt (halite) beds and an intervening argillaceous, anhydritic, fine-grained dolomite. Around the periphery of the basin the D-Unit is thin and consists mainly of shale and anhydrite. It is as much as 60 feet thick in the central basin area but thins to less than 15 at the margins of the basin (Tremper, 1973) (fig. 2.25).

Characteristics as an Aquifer. The D-Unit is not an aquifer.

Characteristics as a Confining Layer. In the basinal areas where the D-Unit salts are present the D-Unit is an aquiclude. Marginal to the area of salt development, the shaly anhydrite should be an aquitard, but would not form as formidable a barrier to the movement of fluids as a thick bed of salt (NaCl).

Characteristics as an Injection Formation. None.

Porosity. Extremely slow.

Permeability. Extremely slow.

Oil and Gas Potential. None.

E-Unit

The Salina E-Unit is a mixture of lithologies. Dominated by shales, it also contains dolomite beds that are locally oolitic and thin beds of anhydrite. It is more than 160 feet thick in the center of the Michigan Basin and thins to less than 90 feet in marginal areas (Tremper, 1973) (fig. 2.26).

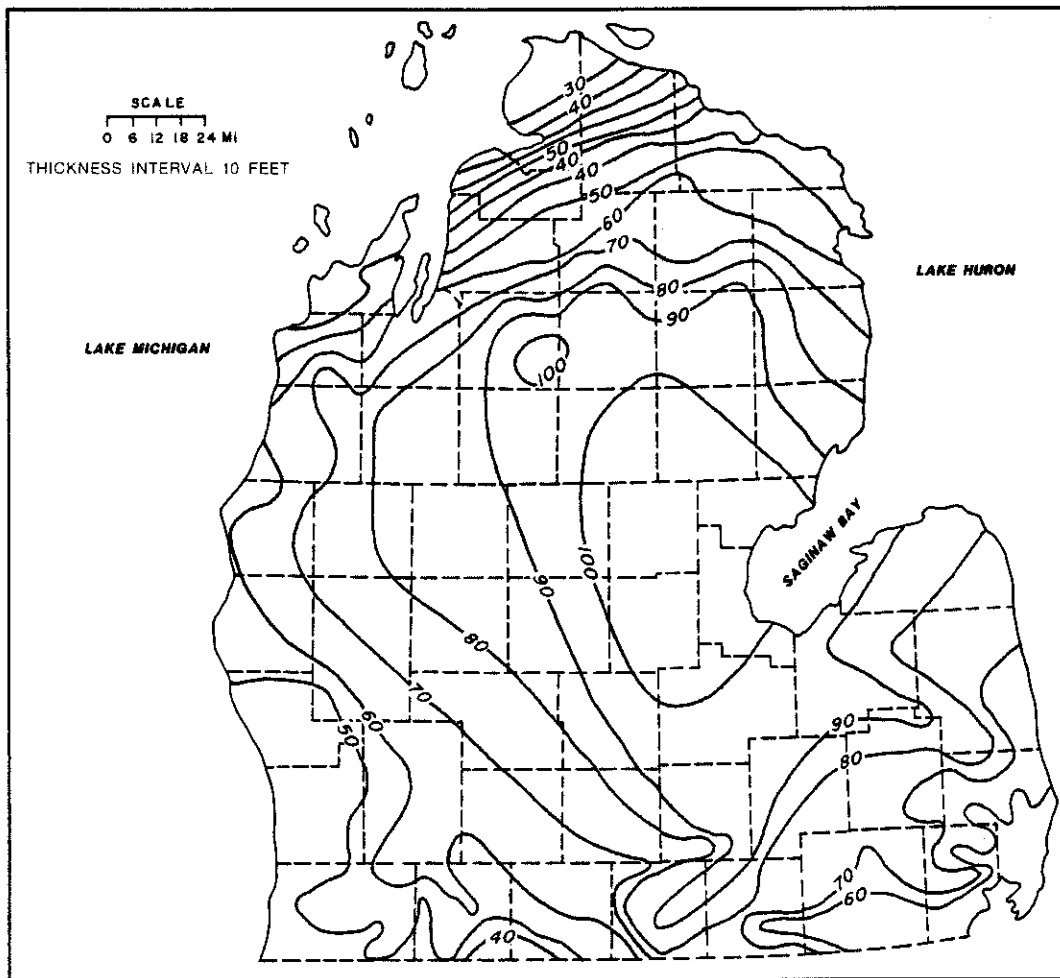


Figure 2.24. Thickness of Salina C Unit. (From Dali, 1975.)

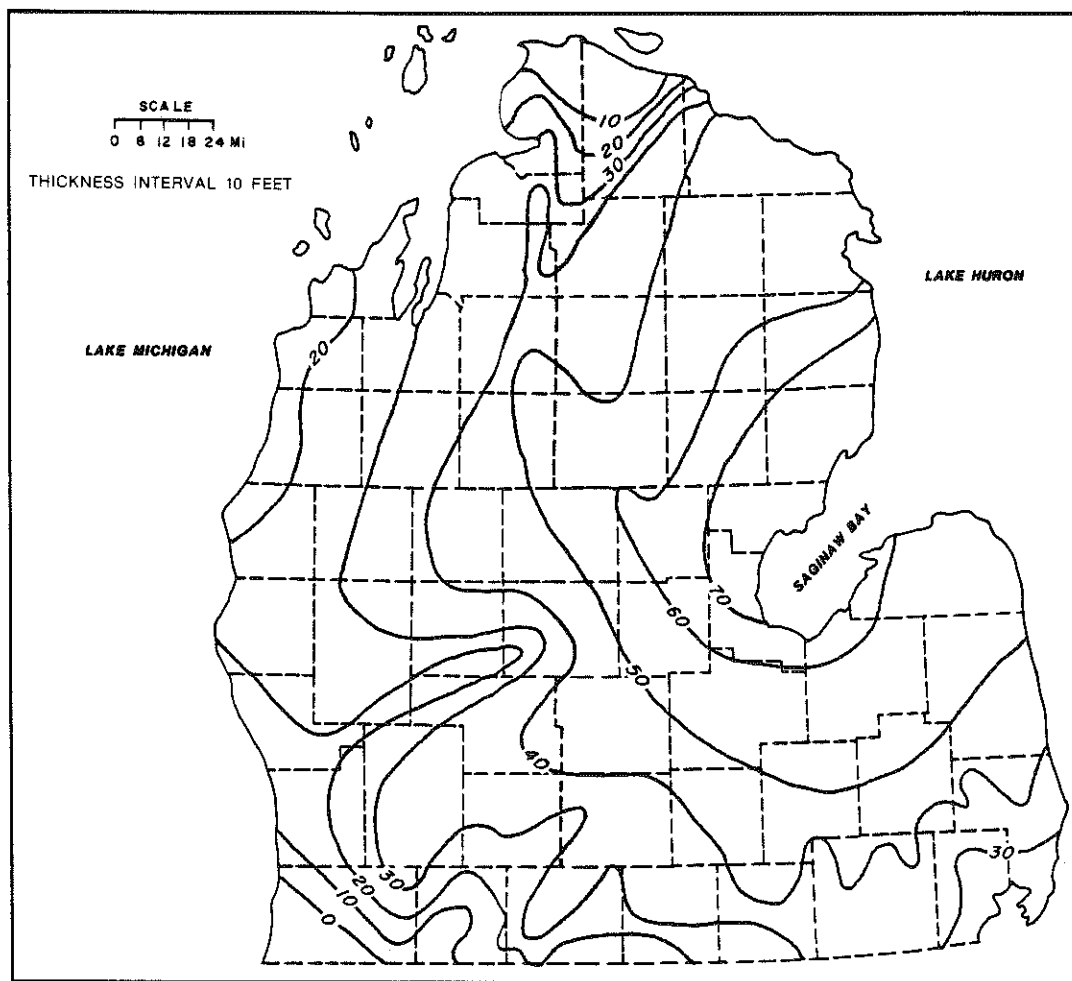


Figure 2.25. Thickness of Salina D Evaporite. (From Dali, 1975.)

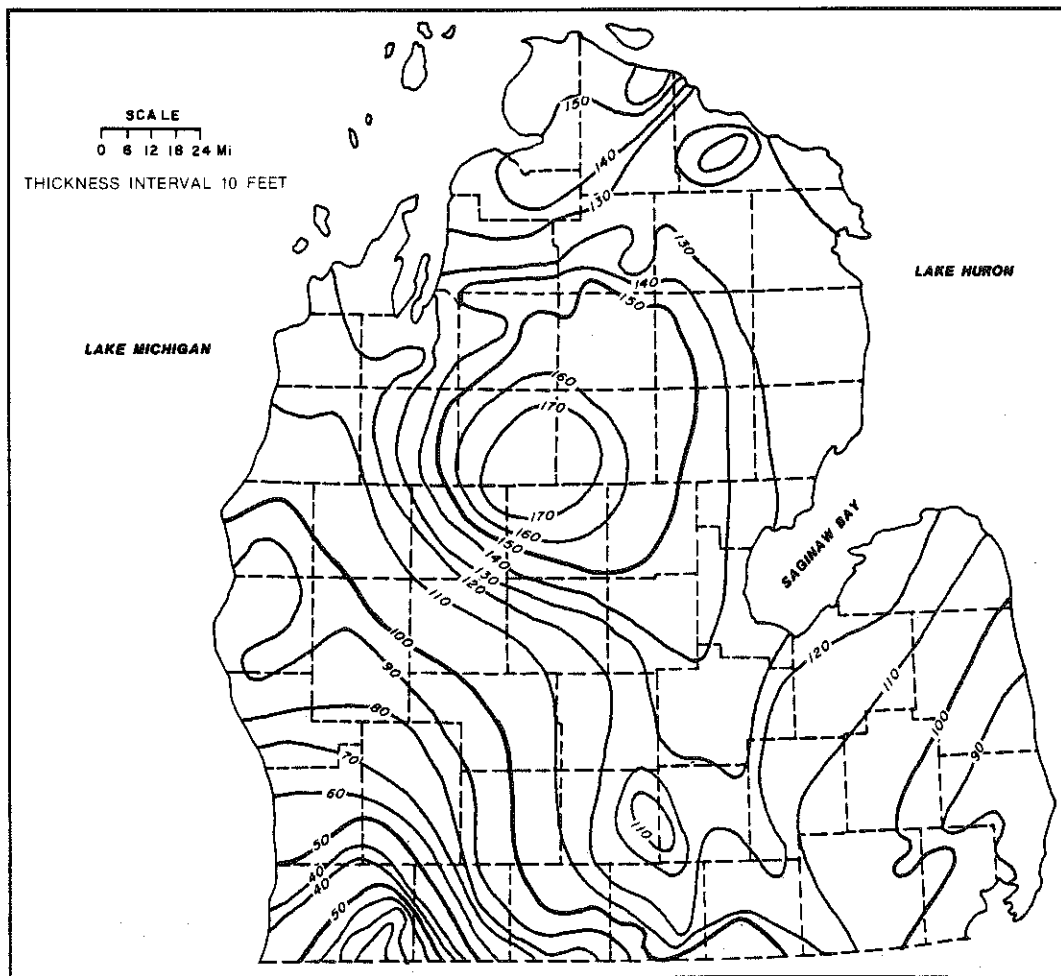


Figure 2.26. Thickness of Salina E Unit. (From Dali, 1975.)

Characteristics as an Aquifer. The E-Unit is not an aquifer.

Characteristics as a Confining Layer. Shales and anhydrite beds in the E-Unit should form a barrier to the migration of fluids. In the central portions of the basin the dolomite beds are most likely salt plugged and also form aquicludes. In areas marginal to salt development, the dolomite beds may permit vertical migration of fluids.

Characteristics as an Injection Formation. Generally unsuitable.

Porosity. Effective porosity of this unit is very low, especially in areas where salt plugging occurs. Marginal to the areas of salt development, the dolomite beds may contain some effective void space. Shales in this unit contain a high ineffective porosity associated with clay minerals.

Permeability. Where salts are developed in the Salina permeability is very low. Marginal to the area of salt development, the dolomite beds are probably permeable.

Oil and Gas Potential. Very low.

F-Unit

The Salina F-Unit comprises a sequence of salt (NaCl) beds with intervening shales and dolomite beds. The top of the unit is generally picked at the top of a buff, fine-grained, anhydritic dolomite. The unit thickens from less than 100 feet on the southwest margin of the basin to over 900 feet at the center of the basin (fig. 2.27). Around the northern margin of the Southern Peninsula the salts are absent and the F-Unit is composed mostly of shale. Southward across the state shale is of diminishing importance in this unit. Shales in the F and G Units probably correlate with the Point aux Chenes Shale in the Salina outcrop belt of the eastern Northern Peninsula.

Characteristics as an Aquifer. The F-Unit is not an aquifer.

Characteristics as a Confining Layer. In the basinal area where salts are present in this unit, and along the northern margin of the Northern Peninsula where the F-Unit is mostly salt, it is an aquiclude. South of the area of salt development the Salina does not contain thick shales and its value as a confining layer is probably minimal.

Characteristics as an Injection Formation. Generally unsuitable.

Porosity. The effective porosity of this unit is very low. Where shales are present, they contain porosity associated with clay minerals.

Permeability. Extremely slow.

Oil and Gas Potential. Extremely low.

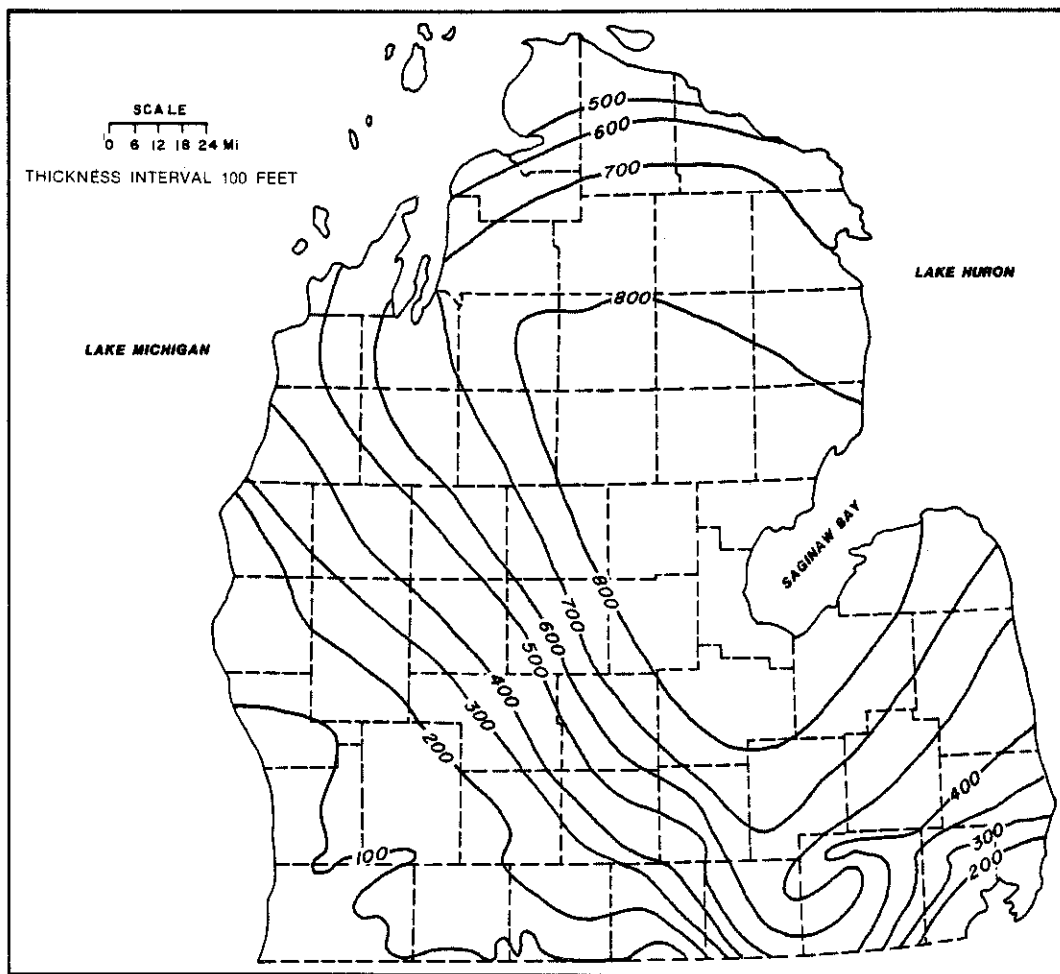


Figure 2.27. Thickness of Salina F Evaporite. (From Dali, 1975.)

G-Unit

The Salina G-Unit is a sequence of dolomitic and anhydritic shales that range in thickness from a zero edge in southern Michigan to more than 100 feet in the northeastern quadrant of the Southern Peninsula (fig. 2.28). This unit is probably correlative with the upper part of the Point aux Chense Shale in the Salina outcrop belt of the eastern Northern Peninsula.

Characteristics as an Aquifer. The G-Unit is not an aquifer.

Characteristics as a Confining Layer. In those portions of the Southern Peninsula where the shales of the G-Unit are more than 40 feet thick it is probably an aquiclude. Marginal to this area (fig. 2.28) its value as a confining layer is probably minimal.

Characterisitcs as an Injection Formation. Generally unsuitable.

Porosity. The effective porosity of the G-Unit is very low.

Permeability. Extremely slow.

Oil and Gas Potential. Extremely low.

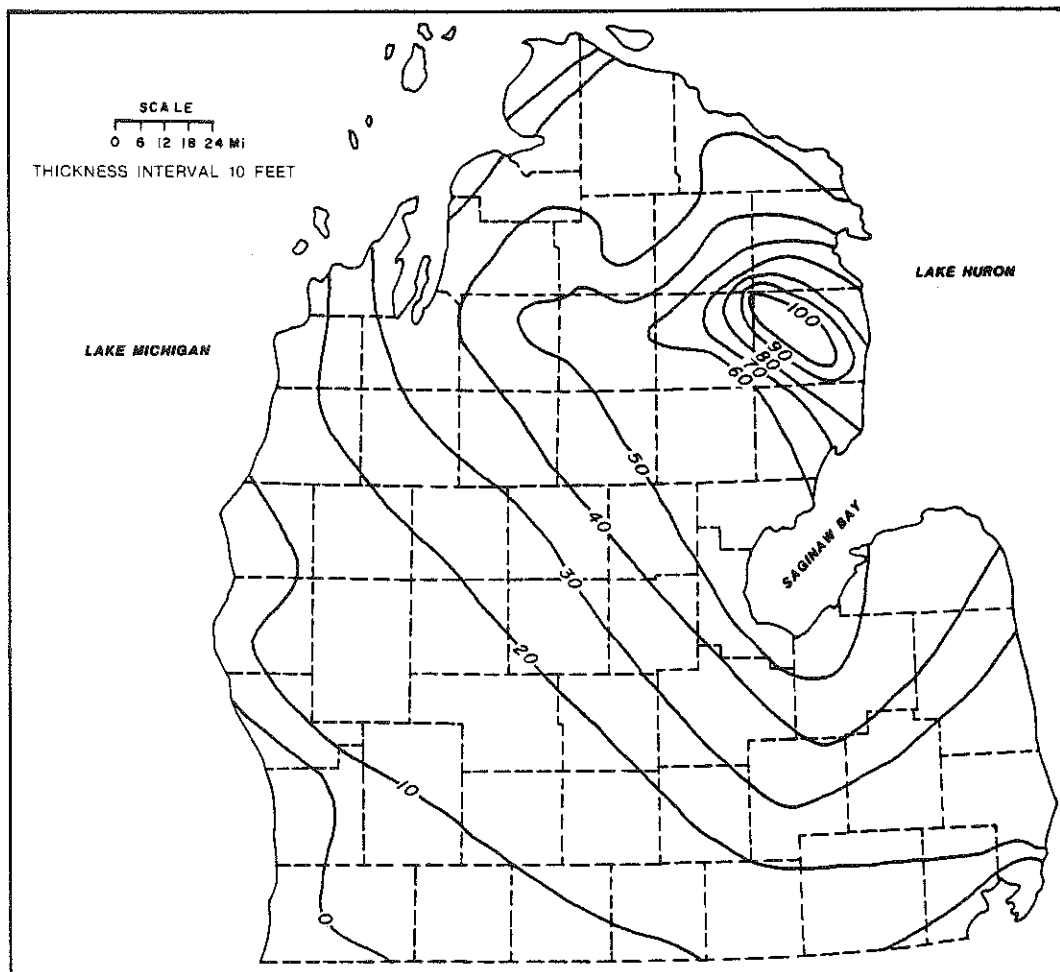


Figure 2.28. Thickness of Salina G Unit. (From Dali, 1975.)

UPPER SILURIAN

The Pointe aux Chenes Shales and the St. Ignace Dolomite comprise the Upper Silurian at outcrop in the eastern Northern Peninsula of Michigan.

Pointe aux Chenes Shale

The Pointe aux Chenes Shale consists of green and red shales, thin beds of dolomite, and small irregular masses and thin seams of gypsum. It is thought to be the equivalent of shales in the F-Unit and G-Units of the subsurface Salina Group. It is likely that it is the lateral equivalent to the shales that exist throughout the column from the B-Unit through the G-Unit.

Characteristics as an Aquifer. The Pointe aux Chenes Shale is not an aquifer.

Characteristics as a Confining Layer. The soft, non-resistant nature of this shale coupled with the presence of gypsum suggests that it is an aquiclude.

Characteristics as an Injection Formation. Unsuitable.

Porosity. Effective porosity is very low. The rock has some porosity associated with clay minerals.

Permeability. Very low.

Oil and Gas Potential. None.

St. Ignace Dolomite

Although placed in the Salina Group by Ehlers and Kessling (1957), the stratigraphic position and lithologic characteristics of this unit clearly suggest that it is the lateral equivalent of the Bass Islands Group. Very likely these rocks are genetically related to rocks of the Salina Group in the same manner that rocks of the Bass Islands Group are related to lithologies in the Salina in more central portions of the Michigan Basin.

The St. Ignace is composed of a evenly bedded dolomite, some of which contains silt-like openings that probably resulted from the solution of anhydrite crystals. Beds of shale ranging from a few inches to a few feet thick are an inconspicuous part of the formation. The upper part of the St. Ignace consists of thick-bedded dolomites that are locally oolitic. Frosted quartz grains are present throughout the formation, but are larger and more abundant near the top.

Characteristics as an Aquifer. Possible source of drinking water on Bois Blanc and Round Islands.

Characteristics as a Confining Layer. Unsuitable.

Porosity. Solution porosity.

Permeability. Solution permeability.

Oil and Gas Potential. None.

Bass Islands Group

At the type sections on the Bass Islands of Western Lake Erie and the outcrop belt in southeastern Michigan, this sequence of dolomites has been subdivided into a number of formations. In the Michigan subsurface it is "lumped" together and referred to as the "Bass Islands". The Bass Islands is a thick sequence of fine-grained dolomites that are characterized by "floating" anhydrite and celestite crystals. In the central portions of Michigan Basin, the Bass Islands contain salt beds, and has been considered an upward continuation of the Salina (Landes, 1945). In the center of the basin, the group exceeds 700 feet in thickness (fig. 2.29).

Characteristics as an Aquifer. Unknown.

Characteristics as a Confining Layer. The Bass Islands should serve as a confining unit throughout much of the Southern Peninsula.

Characteristics as an Injection Formation. Unknown.

Porosity and Permeability. Around the margins of the Michigan Basin the Bass Islands Group has been affected by dissolution and the porosity and permeability greatly increased. Leaching of the relatively soluble anhydrite crystal laths is readily apparent in wells that penetrate these rocks in the northernmost part of the Lower Peninsula. Down dip from this leached zone, dolomites of the Bass Islands are much less soluble and in the area of salt development this unit is only slowly permeable.

DEVONIAN

LOWER DEVONIAN

Garden Island Formation

The Garden Island Formation is known only from isolated patches in the northern part of the Lower Peninsula and at the type section on Garden Island. At the type locality only three feet of dolomitic sandstone, dolomite with frosted sand grains, and hard dolomite with chert nodules is exposed above lake level (Ehler, 1945, p. 73-80).

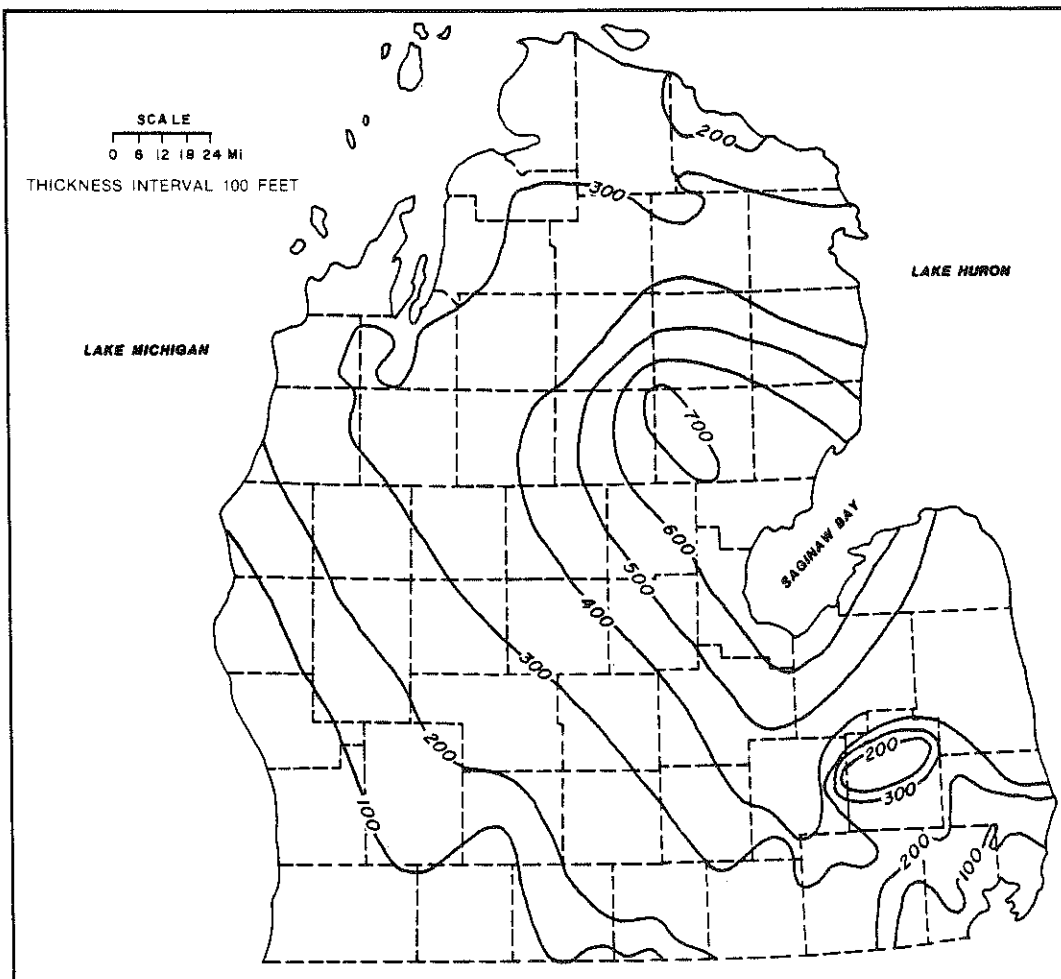


Figure 2.29. Thickness of Bass Islands Group. (After Dali, 1975.)

Characteristics as an Aquifer. Unknown.

Characteristics as a Confining Layer. Unknown. Discontinuous nature of the unit coupled with the presence of sandstone and dolomite do not recommend it as a confining layer.

Characteristics as an Injection Formation. Discontinuous nature of the Garden Island Formation suggests that it would be an inadequate injection formation.

Porosity and Permeability. Unknown.

MIDDLE DEVONIAN

Bois Blanc Formation

From its truncated margin at outcrop in the area of Mackinac Straits the Bois Blanc Formation increases to a maximum thickness of more than 600 feet in Arenac and Gladwin Counties (Cohee, et al., 1951) (fig. 2.30, pls. 5, 6 and 11). The basal 75 feet of the unit is dolomite with interbeds of chert and is overlain by about 200-300 feet of very cherty dolomite and limestone. The upper 75 feet of the unit is fossiliferous limestone.

Characteristics as an Aquifer. The Bois Blanc is not used as an aquifer. In and near the outcrop area it has been leached and could be used as a source of water in the area near the Straits of Mackinac. Proximity of the outcrop area to Lake Michigan and the availability of water in the glacial aquifer have made the use of this aquifer unnecessary to date.

Characteristics as a Confining Layer. Away from the outcrop area the Bois Blanc is very dense and should form a barrier to the movement of fluids. The cherty dolomites are likely to be quite brittle and may have some fracture porosity and permeability. The unit was involved in the subsidence that produced the Mackinac Breccia, and it is very likely highly fractured in the area where this process has occurred (pl. 18).

Characteristics as an Injection Formation. The Bois Blanc Formation is unsuitable for use as an injection formation.

Porosity. Very low.

Permeability. Unknown. Fracture porosity may be present.

Oil and Gas Potential. Low.

Sylvania Sandstone

The Sylvania Sandstone is composed of well-rounded and sorted, fine (0.18 mm) to medium (0.40 mm) grained quartz grains notably free of clay. The sandstone overlies dolomites of the Bass Islands Group with distinct

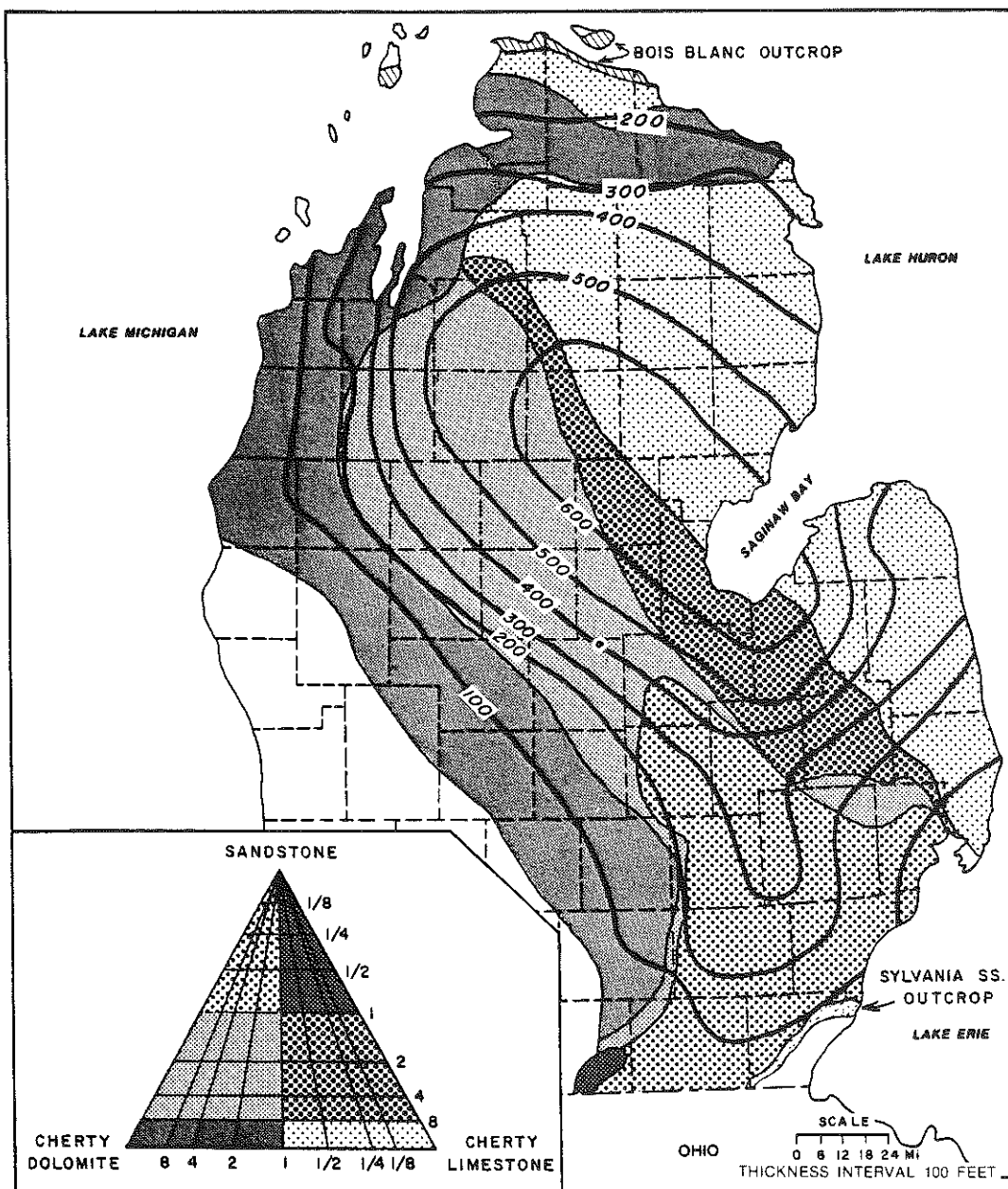


Figure 2.30. Thickness-lithofacies map of Bois Blanc-Sylvania.
(From Gardner, 1974.)

disconformity along the northern margin of its development in northern Ohio and southeastern Michigan. To the north where the Bois Blanc Formation is the basal unit of the Middle Devonian, the Sylvania Sandstone interfingers with cherty carbonates. Contact with the overlying Detroit River beds is transitional from sandstone to dolomitic sandstone to sandy dolomite to dolomite. To the northwest in Wexford, Grand Traverse, Missaukee and Kalkaska Counties, the Sylvania contains thick deposits of tripolitic (de-vitrified) chert with amber dolomite rhombohedrons. The Sylvania outcrops in southeastern Michigan and ranges in thickness from a zero edge in southern Michigan to more than 500 feet in the central part of the Michigan Basin (fig. 2.30).

Characteristics as an Aquifer. In and near the outcrop area where it has been flushed the Sylvania Sandstone is a good aquifer, but because it is overlain by glacial lake beds, composed of silt and clay, water in it commonly contains methane and hydrogen sulfide.

Characteristics as a Confining Layer. The Sylvania is far too permeable to be a confining layer.

Characteristics as an Injection Formation. In areas where the Sylvania is overlain by the anhydrite of the Detroit River, it is a potential injection formation and has been used for both chemical and brine disposal. Care should be taken to avoid areas near the outcrop as the overlying carbonate section may have fracture permeability.

Porosity. High effective porosity exists away from the upper transition with the Detroit River and southwest of the area where the Sylvania and Bois Blanc interfinger.

Permeability. Permeability is very high in those portions of the unit that are free of carbonate and chert cement (see above).

Potential for Oil, Gas and Brine Production. No oil or gas fields have been developed in the Sylvania. It is used extensively as a source of brine especially in the vicinity of Midland County.

Amherstburg

The Amherstburg is a dark brown to black, carbonaceous limestone throughout most of the basin, but around the southern and western margins of the Southern Peninsula it has been dolomitized. The informal name "Black Limestone" has been in use for many years as a driller's term. The lithology is very distinctive in the central-basin area, and was used as a marker at which to bottom exploratory tests into the Richfield zone of the Detroit River. The unit is poorly bedded, dense, and ranges in thickness from a zero edge in southwestern Michigan to more than 300 feet in the area of Saginaw Bay (fig. 2.31).

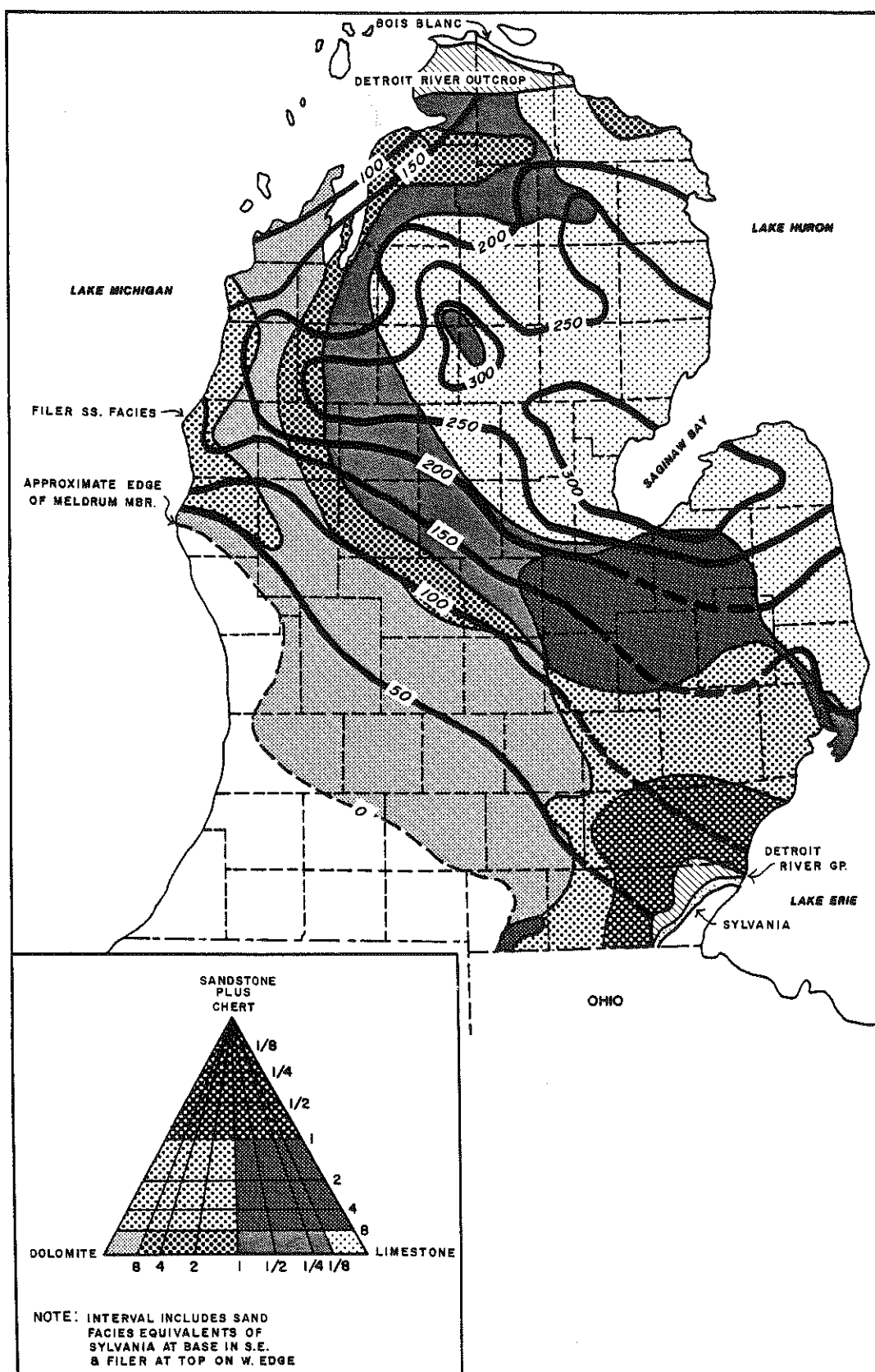


Figure 2.31. Thickness-lithofacies map of Meldrum Member of Amherstburg Formation. (From Gardner, 1974.)

Characteristics as an Aquifer. The Amherstburg is not an aquifer.

Characteristics as a Confining Layer. Except where dolomitized, the Amherstburg is an aquiclude and could be used as a confining layer, in the central portion of the Michigan Basin.

Porosity. The effective porosity of the Amherstburg is low where it is dolomite and very low where it is limestone.

Permeability. The Amherstburg has very low permeability where it is dolomite and is virtually impermeable in those areas where it is a limestone.

Oil and Gas Potential. Very low.

Filer Sandstone Member

The Filer Sandstone is best developed along the western margin of the Southern Peninsula in the area of Manistee. The Filer is a fine to medium grained, quartz sandstone that appears to have been deposited as coastal dunes. Local lenticular sandstone bodies in the central part of the basin appear to be roughly correlative with this unit, and one such unit has been named the Freer Sandstone after a well that penetrated it.

Characteristics as an Aquifer. The Filer Sandstone has excellent aquifer characteristics, but it contains brine.

Characteristics as a Confining Layer. The Filer is far too porous and permeable to be used as a confining layer.

Characteristics as an Injection Formation. The Filer has excellent injection formation characteristics and is used as an injection formation in Michigan.

Porosity. The formation has up to 25 percent effective porosity.

Permeability. Very high.

Oil, Gas and Brine Potential. The Filer has been explored for oil and gas, but to date no sustained production has been developed. The Freer Sandstone had a "one-well" field developed in it. The Filer is a source of brine in the Manistee area.

Detroit River

Although the Bois Blanc Formation, Sylvania Sandstone, Amherstburg (Black Limestone), Lucas and Anderdon Formations have been included in the Detroit River Group, general practice is to call that portion of the column between the Amherstburg (Black Limestone) and the Dundee Limestone the "Detroit River," although it has been named the Lucas Formation. This suite of rocks is quite complex and contains a wide variety of lithologies including sandstone, limestone, dolomite, anhydrite (or gypsum) and halite (figs. to). The Basal unit of the "Detroit River" is the "Richfield zone" or more properly the Richfield Member.

Richfield Zone

The Richfield zone is a sequence of interbedded limestone, dolomite, and anhydrite with minor amounts of sand in the central portion of the basin and a relatively thick sand body, the Filer Sandstone, along the western margin of the Lower Peninsula (fig. 2.32). The limestone beds are dense micrites and contrast with the dolomites which are lighter in color and more permeable. The anhydrite beds have mosaic textures and generally overlie the dolomitized units.

Characteristics as an Aquifer. The Richfield zone is not an aquifer.

Characteristics as a Confining Layer. The anhydrites of the Richfield zone are excellent confining layers. The fact that several of the dolomite zones produce oil attests to the impervious nature of the interbedded anhydrites.

Characteristics as an Injection Formation. The Richfield contains too little permeable rock to be an injection formation.

Porosity. The dolomite zones in the Richfield are slightly porous, but the limestones and anhydrite beds essentially lack porosity.

Permeability. The limestone and anhydrite beds are virtually impermeable. The dolomite units have permeabilities that range from 4.0 to 6.5 milli-darcys.

Oil and Gas Potential. The Richfield has produced oil and gas from several fields in Michigan since the early 1940's.

Massive Anhydrite

The driller's term "Massive Anhydrite" has been traditionally applied to a thick (75-100 feet) anhydrite bed that overlies the Richfield Zone (fig. 2.33). The unit is widespread in the central portions of the basin and thins toward the basin margins. It is best developed in the north-central part of the Southern Peninsula.

Characteristics as an Aquifer. The Massive Anhydrite is not an aquifer.

Characteristics as a Confining Layer. The Massive Anhydrite is essentially impermeable and an excellent confining unit.

Characteristics as an Injection Formation. None.

Porosity. Extremely low.

Permeability. Extremely low to essentially impermeable.

Oil and Gas Potential. None.

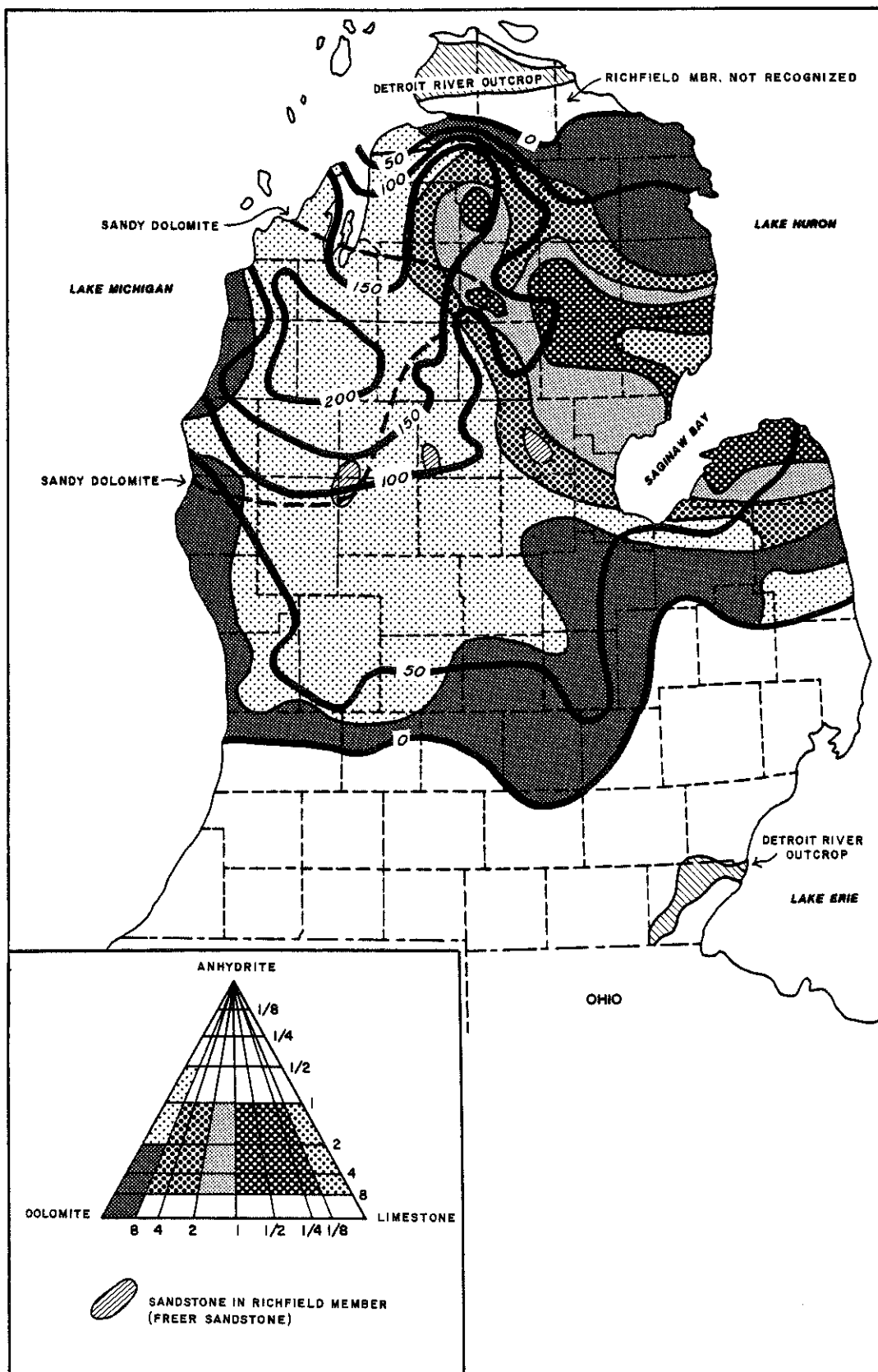


Figure 2.32. Thickness-lithofacies map of Richfield Member of Lucas Formation. (From Gardner, 1974.)

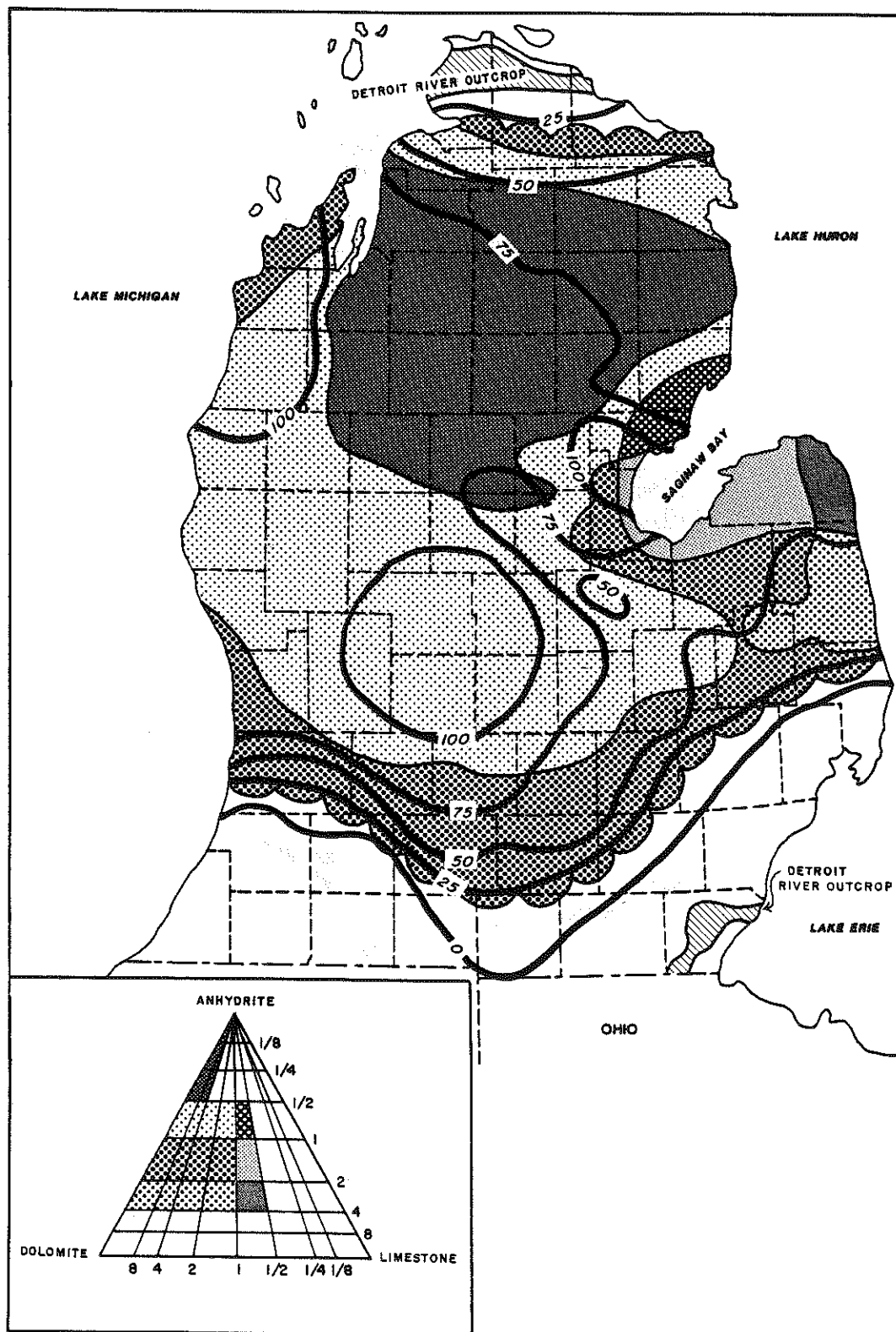


Figure 2.33. Thickness-lithofacies map of the "Massive Anhydrite" of Iutzi Member. (From Gardner, 1974.)

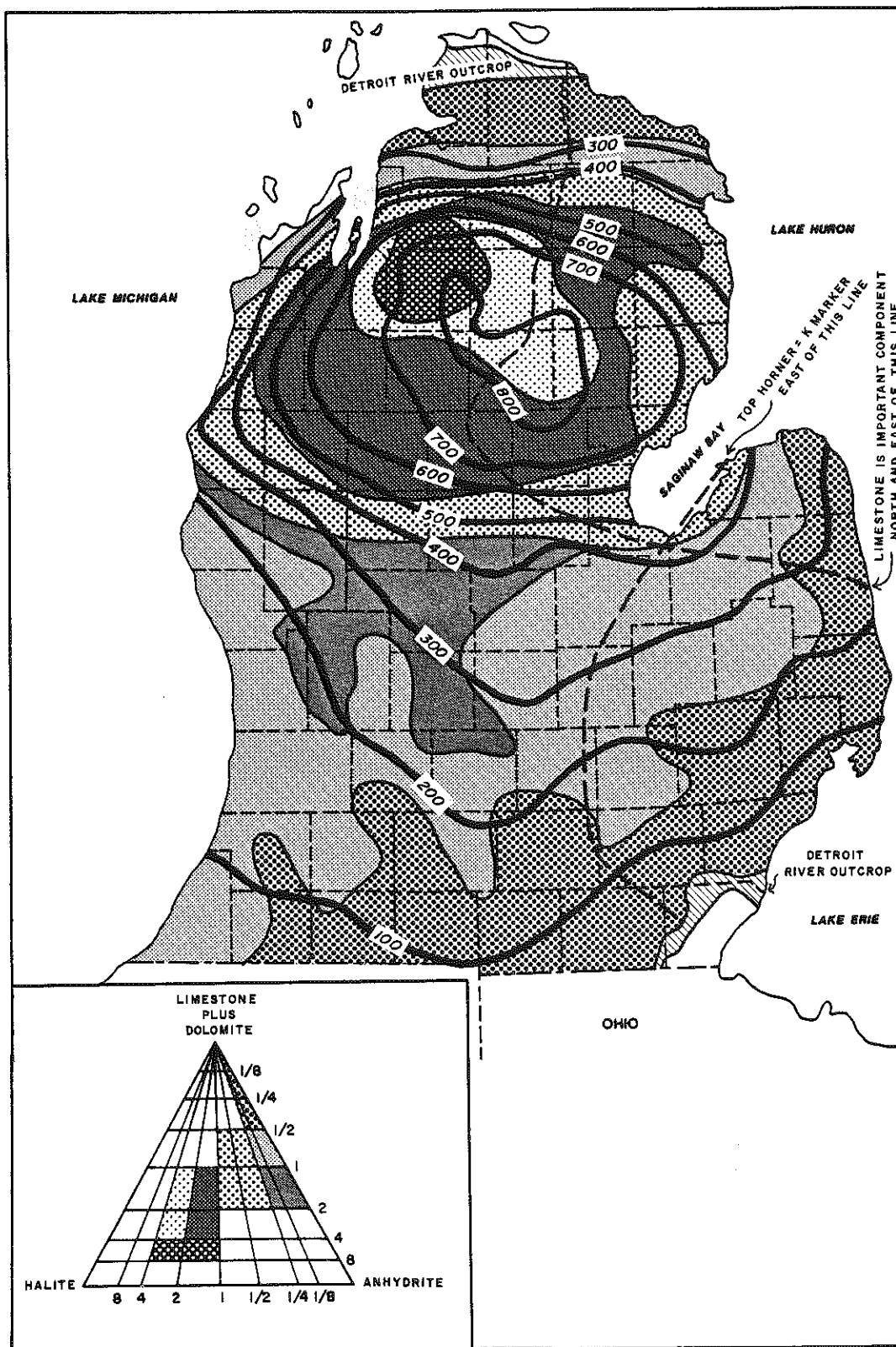


Figure 2.34. Thickness-lithofacies map of the Horner Member of Lucas Formation. (From Gardner, 1974.)

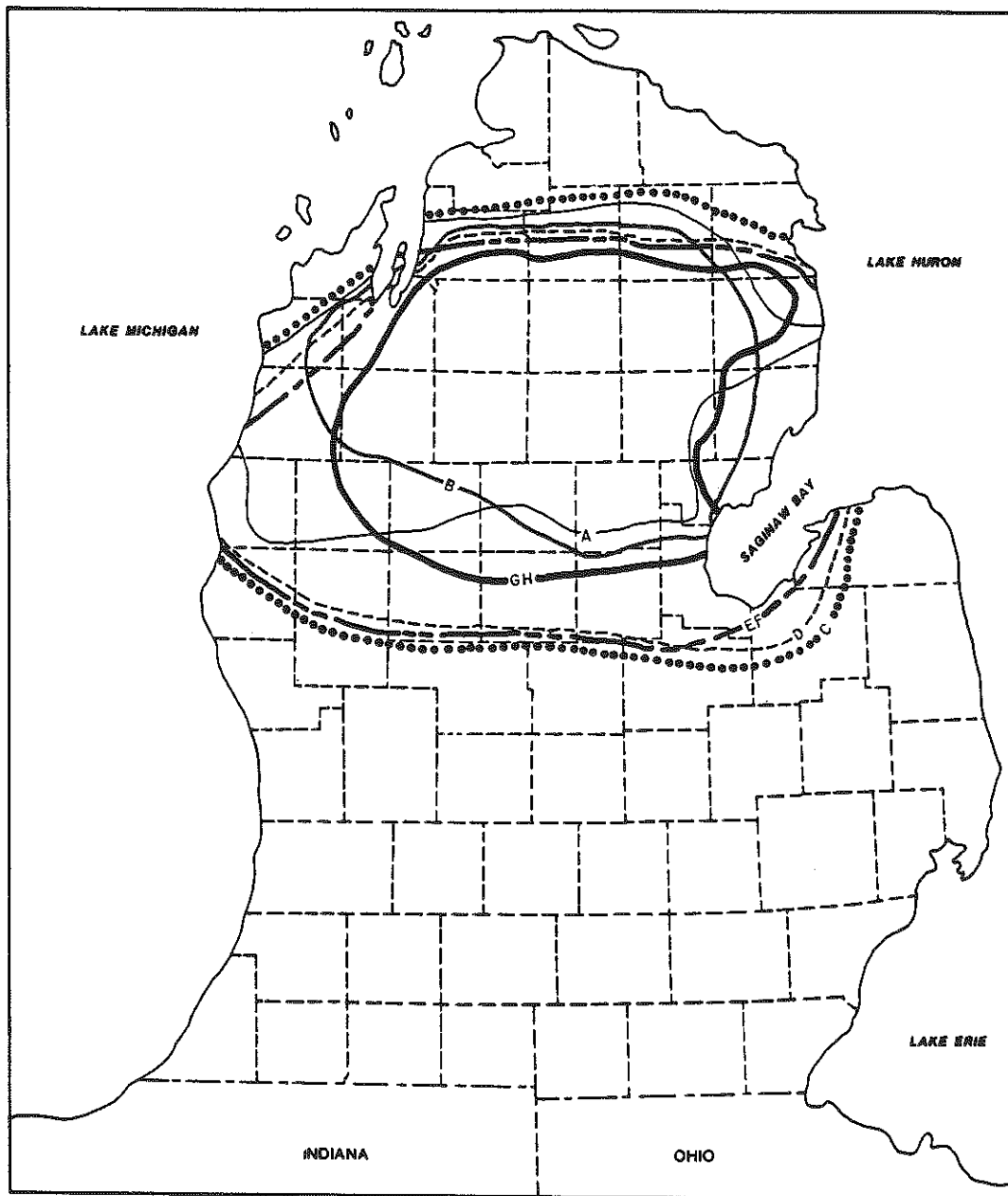


Figure 2.35. Distribution of Horner Salts A through H. (From Gardner, 1974.)

Horner Evaporite Member of the Lucas Formation

The massive anhydrite is overlain by a thick halite-bearing evaporite sequence, the Horner Member consisting of a repetitive series of limestone, anhydrite and salt beds that may represent cyclic deposition (fig. 2.34 and 2.35). The unit includes up to 450 feet of salt in 8 distinct beds. The salts are located between T 11N and T 33N in the northern Southern Peninsula. Anhydrite beds in the Horner Member extend from just south of the Straits of Mackinac (about T 33N) south into Indiana.

Characteristics as an Aquifer. The lithologies in the Horner Member, salt, limestone, anhydrite, dolomite, are generally too impermeable to contain much water. In areas where the dolomite beds are permeable they generally contain brine. Where salts are developed, the brines are highly sulfurous and over structures in the center of the basin some contain sulfurous oil.

Characteristics as a Confining Layer. The Horner Member is an excellent confining unit. Evaporite beds, anhydrite and salt are among the most impermeable sedimentary units in the State.

Characteristics as an Injection Formation. In the area of salt development, dolomite beds in the lower Horner will accept limited amounts of fluids. South of the area of salt development, dolomite beds in the Horner will accept fluids.

Porosity. The salt and anhydrite are essentially nonporous. The limestone has a very low porosity and the dolomite has a low to moderate porosity.

Permeability. Only the dolomite beds in the Horner have a measurable permeability under normal pressures, and this is generally quite low. In the southern third of the Southern Peninsula, several dolomite beds in the Horner portion of the Detroit River are quite permeable.

Oil and Gas Potential. Oil is produced from the Horner "Sour Zones" in the north-central portion of the Southern Peninsula. The production is limited, but it is sufficient to cause this unit to be considered prospective.

Reed City Zone

In the older literature the Reed City Zone was considered to be part of the uppermost Detroit River. Recently it has been related to the overlying Dundee Limestone. Although its stratigraphic affinities are in question, the Reed City Member consists of an easily recognized anhydrite and underlying porous dolomite. The Reed City Member is present in the

western Southern Peninsula from Cadillac south into Indiana. Throughout the eastern margin of this area the anhydrite is underlain by a porous and permeable dolomite generally referred to as the "Reed City Zone". Gardner (1974) suggested that the Reed City dolomite and anhydrite are the western equivalents of the Dundee Limestone, and that they represent the westward movement of the evaporite forming conditions that existed in the Michigan Basin during deposition of the Detroit River. According to this view the Dundee is conformable with the underlying Detroit River.

Characteristics as an Aquifer. Throughout its extent in Michigan, the Reed City dolomite is filled with brine and/or hydrocarbons. The anhydrite is too impermeable to contain significant amounts of fluid.

Characteristics as a Confining Layer. The Reed City dolomite is too permeable to be a confining layer, but the overlying Reed City anhydrite is an excellent aquiclude.

Characteristics as an Injection Formation. Where the Reed City dolomite does not contain commercial quantities of hydrocarbons, it could serve as an injection formation.

Porosity. The Reed City dolomite is porous to very porous. The Reed City anhydrite essentially lacks effective porosity.

Permeability. The Reed City dolomite is permeable to very permeable. The Reed City anhydrite is essentially impermeable.

Oil and Gas Potential. The Reed City dolomite has produced significant quantities of oil and gas in the western part of the Southern Peninsula.

Dundee Limestone

The Dundee of driller's usage has been subdivided into the Rogers City and Dundee Limestones (Ehlers, 1945; Cohee & Underwood, 1945; Ehlers, et al., 1959; Gardner, 1974). Because the two units are generally undivided by the oil industry they will be discussed here as a single unit, the Dundee Limestone.

The Dundee is a fossiliferous limestone that is locally dolomitized (figs. 2.36 and 2.37). It ranges in thickness from about 150 feet in the western half of the Southern Peninsula to more than 350 feet in the east-central portion of the Michigan Basin. It is locally highly dolomitized, especially over anticlines in the central Michigan Basin.

Characteristics as an Aquifer. The Dundee Limestone is an aquifer in the northern portion of the Southern Peninsula and in its outcrop planes and solutionally enlarged joints. Because the water is present in "selective" porous and permeable zones associated with fractures and bedding planes it is susceptible to pollution. In the central part of the basin the Dundee contains brine and hydrocarbons.

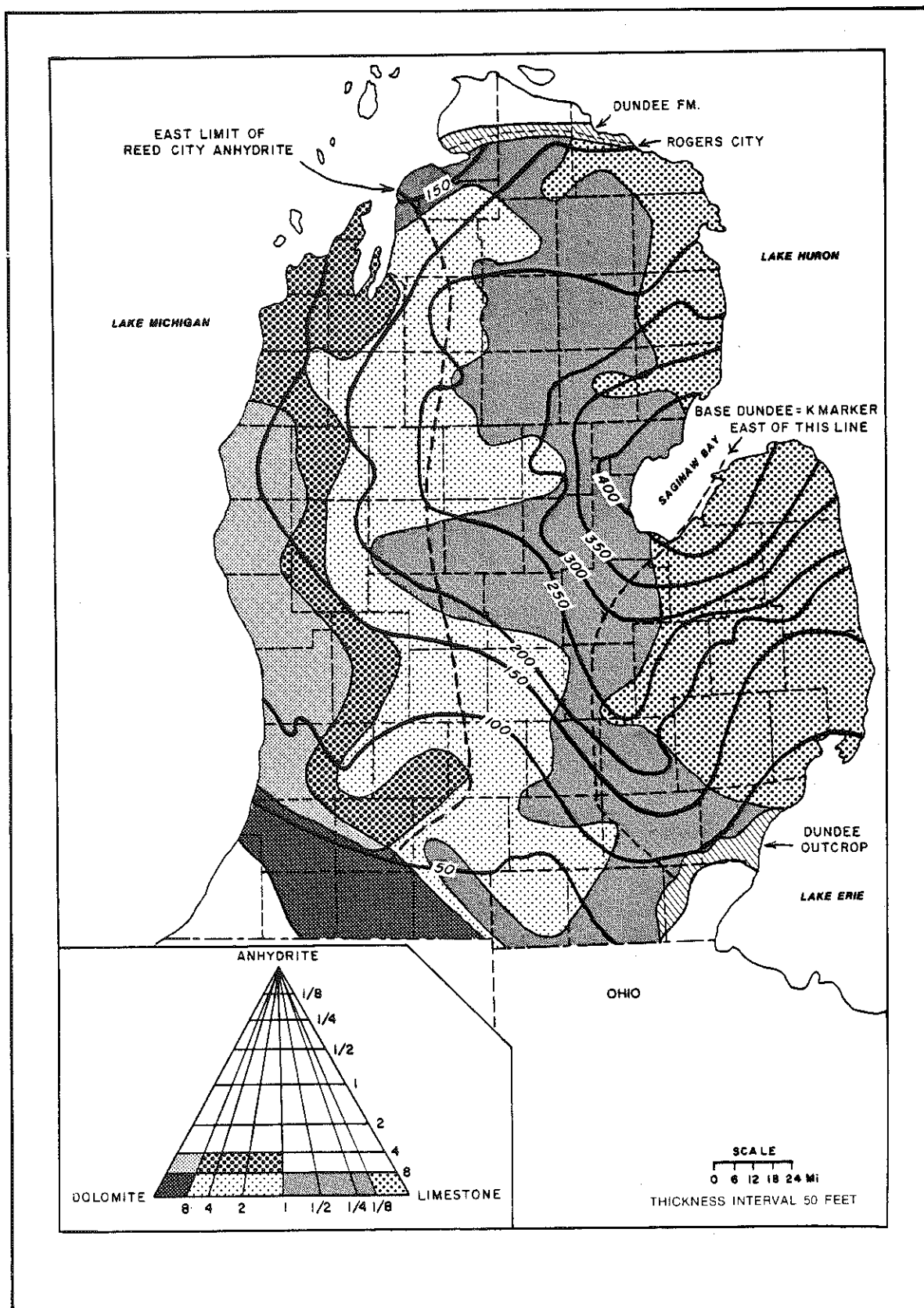


Figure 2.36. Thickness-lithofacies map of Dundee Formation. (From Gardner, 1974.)

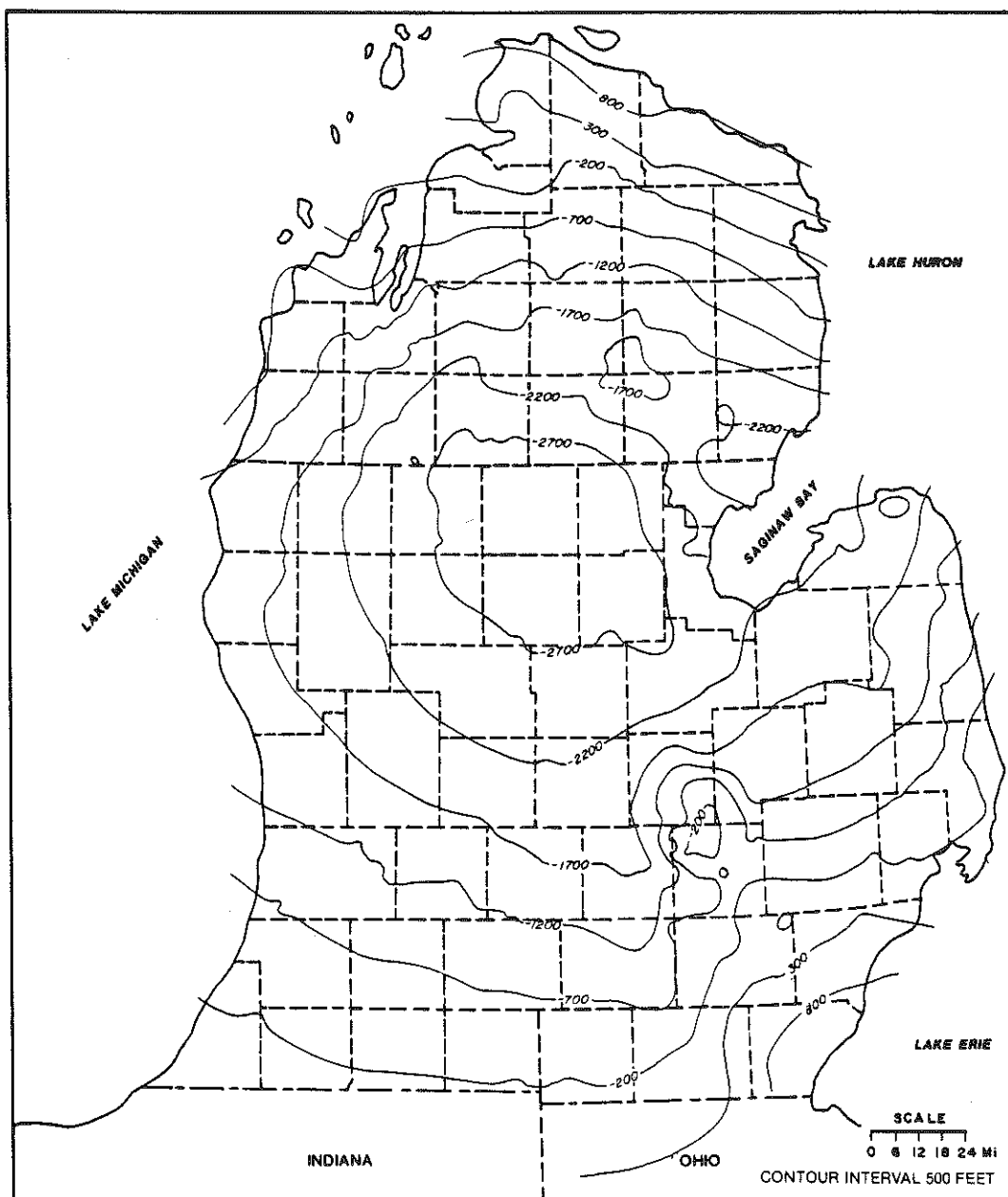


Figure 2.37. Structure map on Dundee Formation. (From Fisher, 1980.)

Characteristics as a Confining Layer. In the eastern third of the Lower Peninsula, the Dundee is dominantly limestone and very slowly permeable. In this area the only limitations to its use as a confining layer is the presence of fractures.

Characteristics as an Injection Formation. In areas where the Dundee has been dolomitized, it could be and is used as an injection formation for chemicals and brine.

Porosity. In areas where the Dundee is limestone, it has very low effective porosity; however, in areas where the Dundee has been dolomitized it is very porous.

Permeability. Where the Dundee is limestone it is very slowly permeable but dolomitized zones are highly permeable.

Oil and Gas Potential. The Dundee has been a prolific oil and gas producer and is a prime target for oil and gas in the central Michigan Basin.

Traverse Group

The Traverse is a thick (100'-800') sequence of alternating shales and limestones in the northeastern two-thirds of the Southern Peninsula (figs. 2.38 to 2.40). In the "Thumb" area shales comprise more than 80 percent of the Traverse Group. In contrast, shale makes up less than 20 percent of the unit in southwestern Michigan. The Traverse has been subdivided in the Alpena and Traverse City areas and, in general, each of the alternating shales and limestone units has been assigned a formation name. To the southwest, the shales thin and the distinctive character of each limestone unit becomes progressively more obscure until it is impossible to distinguish units within the Traverse Group. Even the Traverse-Dundee contact is difficult to discern.

The Traverse crops out and subcrops beneath the glacial drift around the northern margin of the Southern Peninsula and in southeastern Michigan. In the northern outcrop band, the presence of shale or limestone at the surface is an important controlling factor in the potential of the Traverse as an aquifer. Where shales are at the surface, as in the area of Bell Shale (basal Traverse Group), bedrock is not generally used as an aquifer. In contrast, outcrop bands of the limestone units form bedrock aquifers.

Characteristics as an Aquifer. The shales in the Traverse Group are not aquifers. The limestone units are "karst" aquifers, and may supply large volumes of water locally. The cavernous nature of these units makes them extremely vulnerable to contamination.

Characteristics as a Confining Layer. The shales in the Traverse Group, especially the Bell Shale, are excellent confining layers. To the southwest, the shales thin and are less adequate barriers to the movement of fluids. The numerous oil and gas fields in the underlying Dundee attest to the impermeable nature of the Bell Shale. The limestone units should not be regarded as aquicludes, especially in and near the outcrop areas.

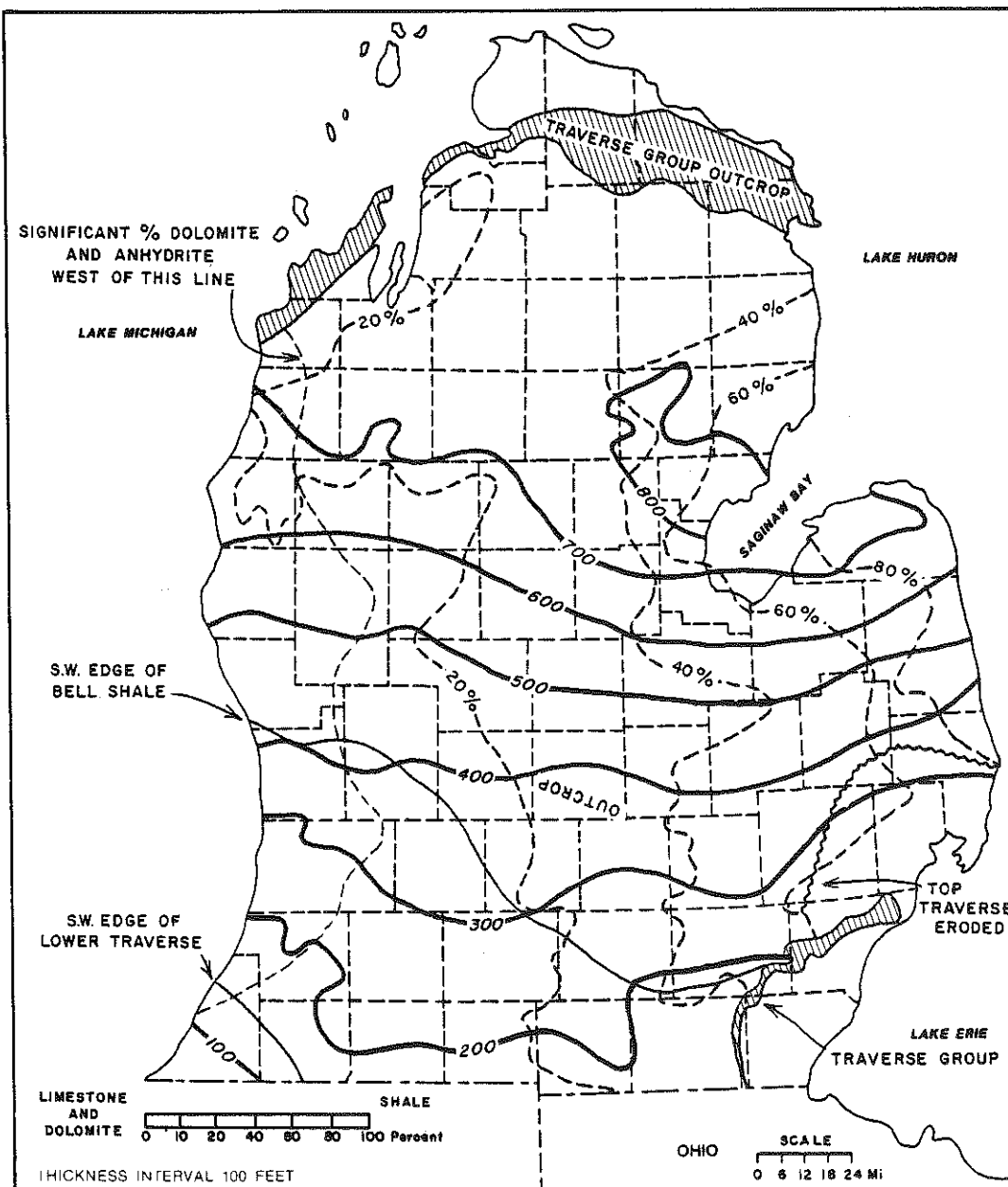


Figure 2.38. Thickness-percent shale map of Traverse Group.
(From Gardner, 1974.)

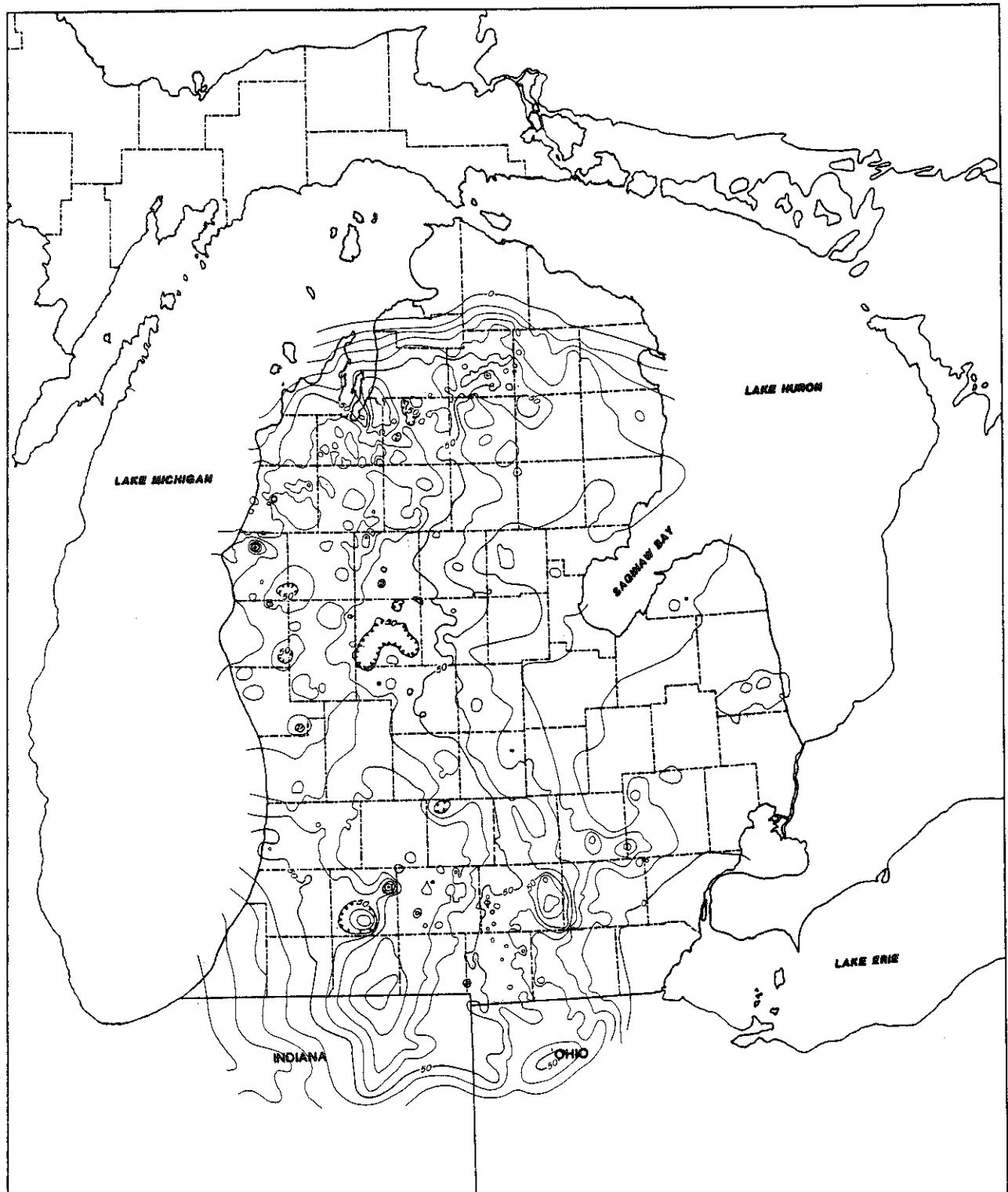


Figure 2.39. Thickness of Traverse Formation. (From Fisher, 1980.)

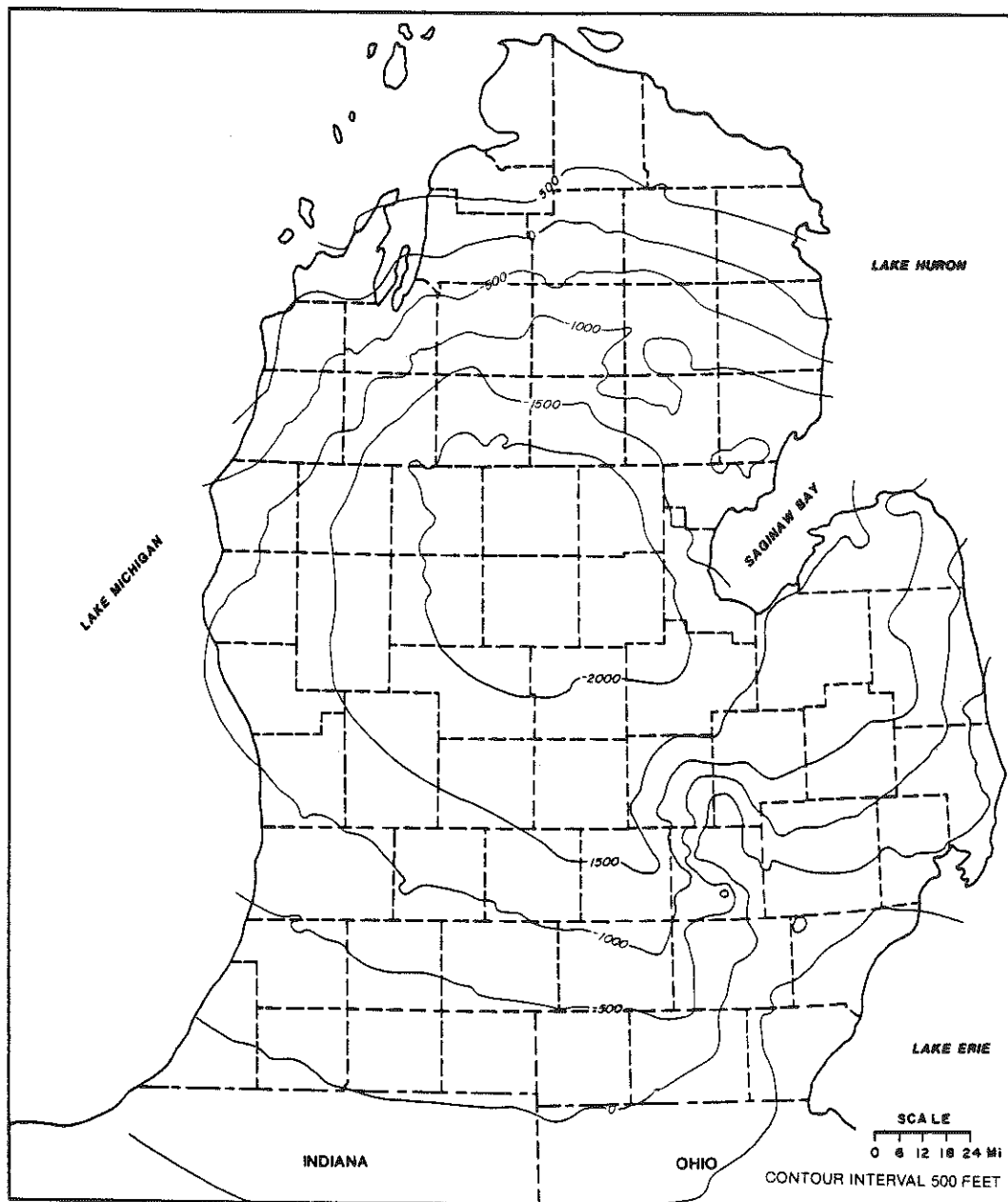


Figure 2.40. Structure map on Traverse Limestone. (From Fisher, 1980.)

Characteristics as an Injection Formation. The Traverse "Limestone" is productive of oil and gas in central and western parts of the Michigan Basin. The porous zones that produce hydrocarbons and brine can be, and are used for injection of fluids, but hydrocarbon potential should be considered when siting Traverse disposal wells.

Porosity. The shales in the Traverse Group generally have very low effective porosity. The limestone units are generally relatively impermeable, but have local porous zones. The uppermost limestone unit in the Traverse, generally referred to as the "Traverse Limestone," or in some reports as the "Squaw Bay," is porous over wide areas of the central and western Michigan Basin.

Permeability. The shales of the Traverse Group are generally impermeable, and the limestones are only locally so. The top few feet of the uppermost Traverse Limestone unit is generally permeable in the central and western parts of the basin.

Oil and Gas Potential. The Traverse Limestone unit produces oil, gas and brine throughout the central and western portions of the basin.

Antrim Shale

The Antrim Shale is a hard, dark gray to black or dark brown, pyritiferous shale that locally contains abundant silt. It ranges in thickness from 120 feet to more than 600 feet (figs. 2.41 and 2.42). In southern Michigan, the basal member of the Antrim is a dark gray dolomite that correlates with the Blocher Member of the New Albany Shale in Indiana. In Michigan this member is referred to as the Traverse Formation. The Antrim Shale is part of the greater "eastern black shale" that includes (1) the New Albany in Indiana; (2) the Ohio Shale in Ohio; and (3) the Chattanooga Shale in Kentucky.

Characteristics as an Aquifer. The Antrim Shale is generally too impermeable to be an aquifer. The low permeability coupled with the presence of abundant pyrite and marcasite generally restrict its use.

Characteristics as a Confining Layer. The Antrim is an excellent confining layer. It forms the seal over most of the Traverse oil fields in Michigan.

Characteristics as an Injection Formation. The Antrim is too impermeable to be used as an injection formation.

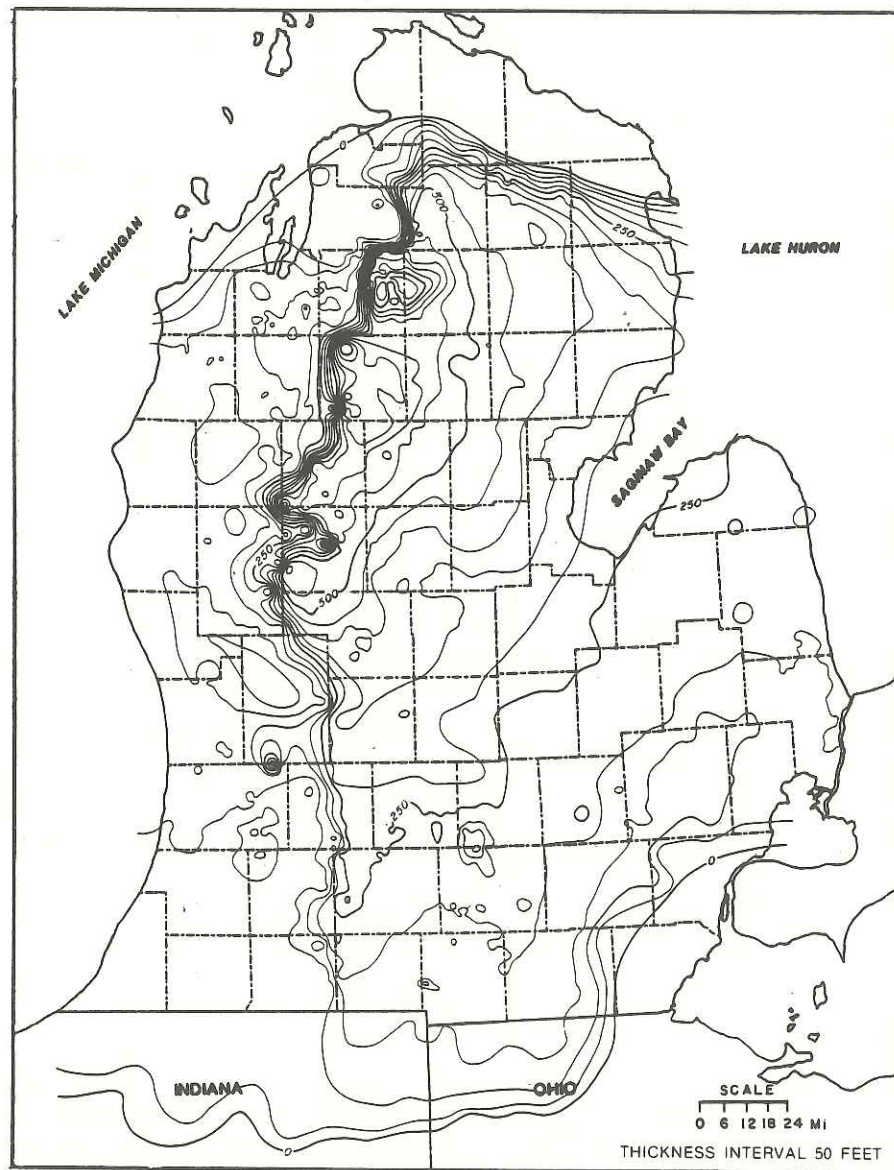


Figure 2.41. Thickness of Antrim Shale. (From Fisher, 1980.)

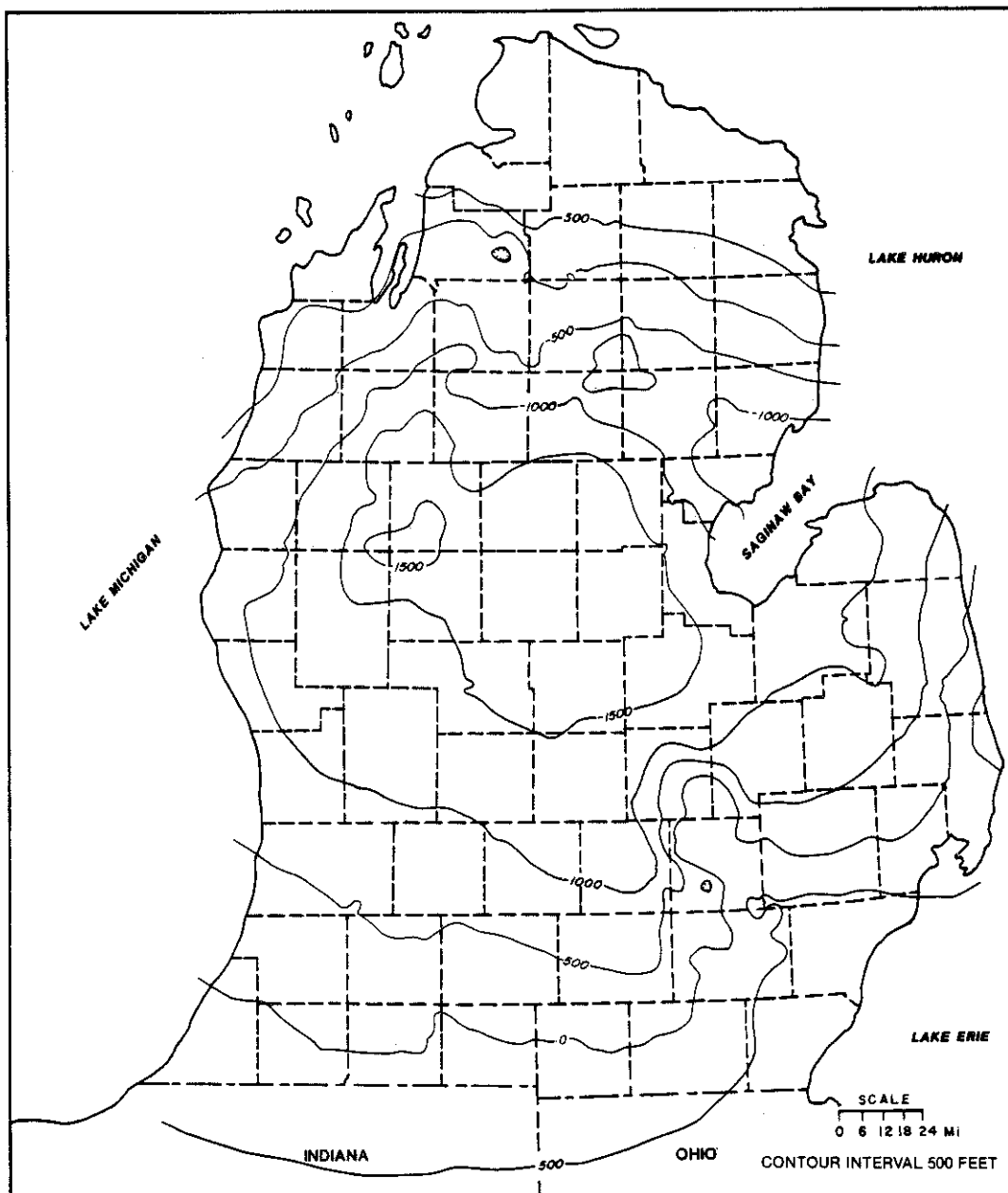


Figure 2.42. Structure map on Antrim Shale. (From Fisher, 1980.)

Porosity. The Antrim Shale has a very low effective porosity.

Permeability. The Antrim Shale generally has a very low permeability. In and near the area of outcrop it is commonly jointed and may have some fracture permeability.

Oil and Gas Potential. The Antrim Shale has produced some gas in Otsego County and it is now considered to be an exploration target for gas. It is also being investigated as a source of hydrocarbons generated by in situ combustion.

Ellsworth Shale

The Ellsworth shale is the lateral facies equivalent of the Antrim. It lacks the carbonaceous aspect of the Antrim, and is not regarded as a possible source of hydrocarbons. Otherwise, it has essentially the same characteristics. The Ellsworth ranges in thickness from 0 to 700 feet and is present only in the western part of the Southern Peninsula (fig. 2.43).

Characteristics as an Aquifer. None

Characteristics as an Aquiclude. The Ellsworth Shale is an aquiclude. It has very low permeability and a low effective porosity.

Characteristics as an Injection Formation. None.

Porosity. The effective permeability of the Ellsworth Shale is very low.

Permeability. The Ellsworth Shale has very low permeability.

Oil and Gas Potential. None.

Bedford Shale

The Bedford is a gray shale that overlies the Antrim Shale in the eastern two-thirds of the Southern Peninsula and intertongues with the Ellsworth Shale in the western part of this area. It ranges in thickness up to 200 feet and is overlain conformably by the Berea Sandstone (fig. 2.44).

Characteristics as an Aquifer. None.

Characteristics as an Aquiclude. The Bedford Shale is an aquiclude. It has very low permeability and a low effective porosity.

Characteristics as an Injection Formation. None.

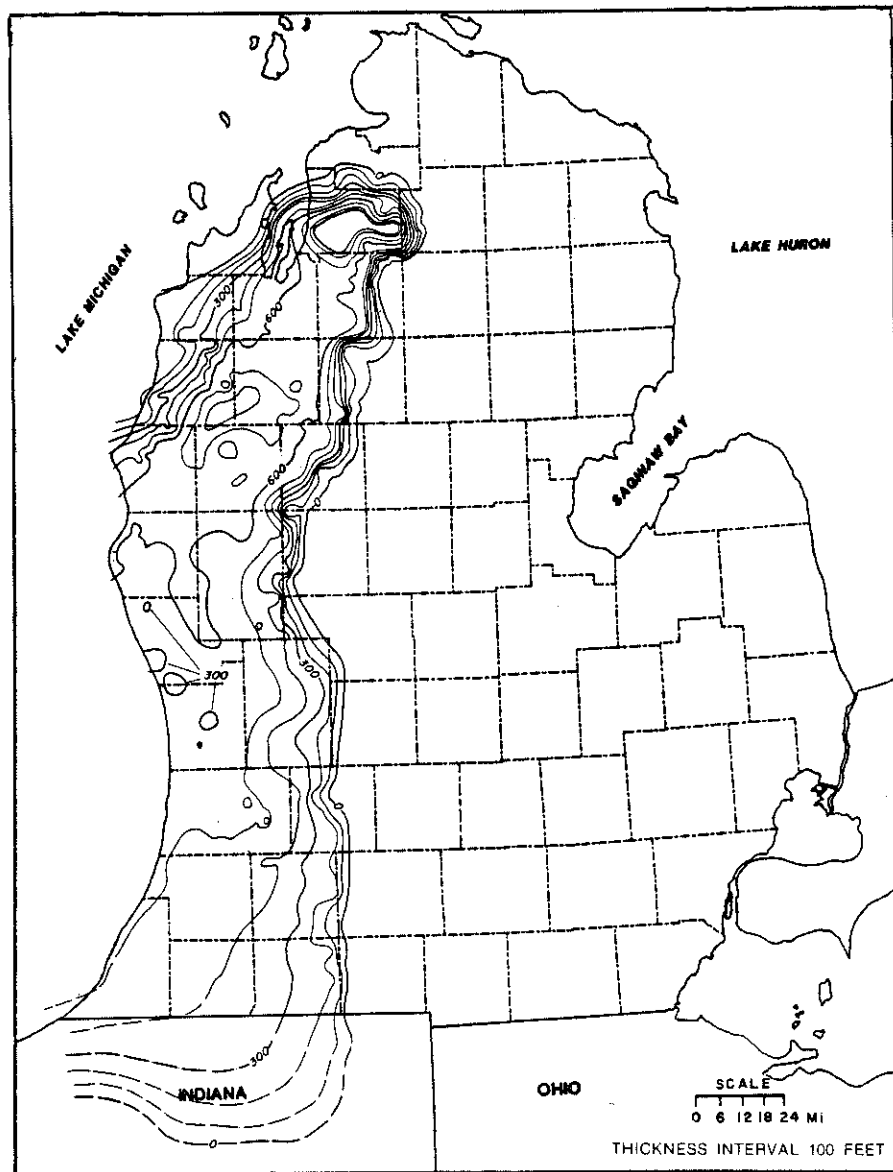


Figure 2.43. Thickness of Ellsworth Shale. (From Fisher, 1980.)

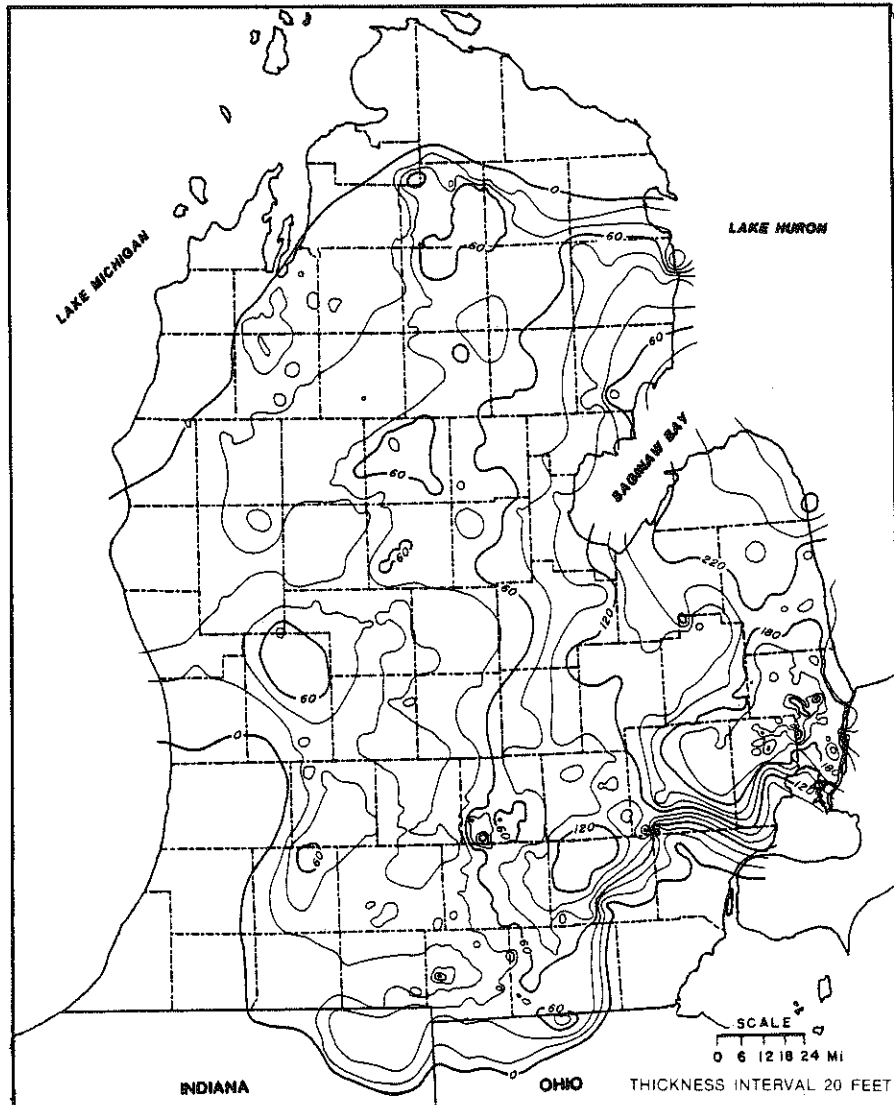


Figure 2.44. Thickness of Bedford Shale. (From Fisher, 1980.)

Porosity. The effective permeability of the Bedford Shale is very low.

Permeability. The Bedford Shale has very low permeability.

Oil and Gas Potential. None.

Berea Sandstone

The Berea Sandstone consists of a moderately fine-grained sandstone that grades upward and downward into shaly, dolomitic sandstone. The Berea is more than 100 feet thick on the east side of the Southern Peninsula and thins progressively to the west. In the central part of the basin, the Berea and Bedford are difficult to distinguish and farther west, the Berea grades into the upper Ellsworth Shale. In the central part of the Michigan Basin the Berea is as much as 1800 feet below sea level (figs. 2.45 and 2.46).

Characteristics as an Aquifer. In eastern Michigan, in and near its outcrop belt, the Berea has good aquifer characteristics.

Characteristics as a Confining Layer. The Berea is too permeable to serve as a confining layer.

Characteristics as an Injection Formation. In and near the outcrop, the Berea is an aquifer and should not be used as an injection formation. In the east-central part of the state it is capable of receiving fluids, but produces hydrocarbons and is relatively shallow.

Porosity. The middle portion of the Berea has good porosity, but the upper and lower parts of the unit are shaly and have a low effective porosity.

Permeability. The middle unit of the Berea is fairly permeable, but the upper and lower zones have a much diminished permeability because of an increased shale content.

Oil and Gas Potential. Several fields in eastern Michigan produce oil and gas from the Berea; however it is not considered to be a prime exploration target.

Sunbury Shale

The Sunbury is a dark gray to black or brown, bituminous, pyritic shale, similar in many respects to the Antrim Shale. It ranges in thickness from 0 feet in parts of the western Southern Peninsula to as much as 140 feet on the eastern side of the state (figs. 2.47 and 2.48). The formation thins from east to west and is the facies equivalent of the upper Ellsworth. The Sunbury reaches a maximum depth of about 1800 below sea level in the center of the Michigan Basin.

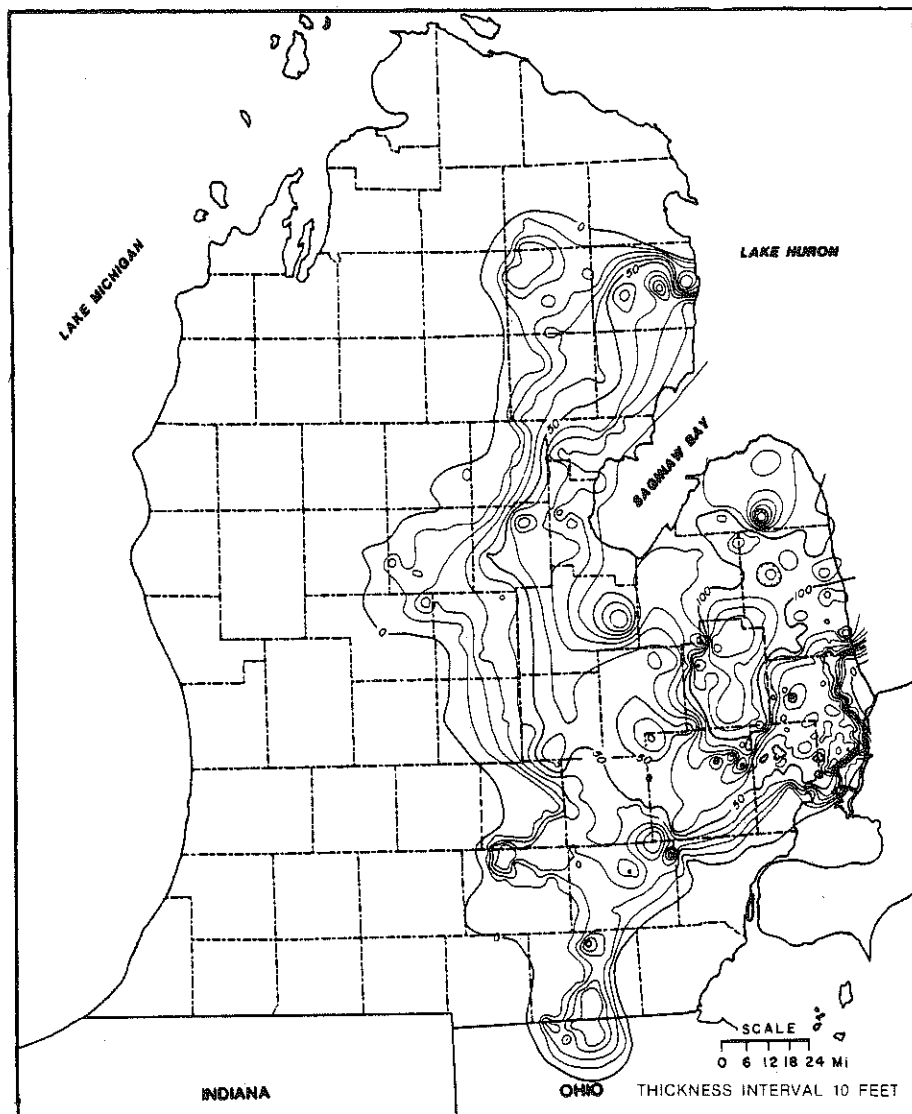


Figure 2.45. Thickness of Berea Sandstone. (From Fisher, 1980.)

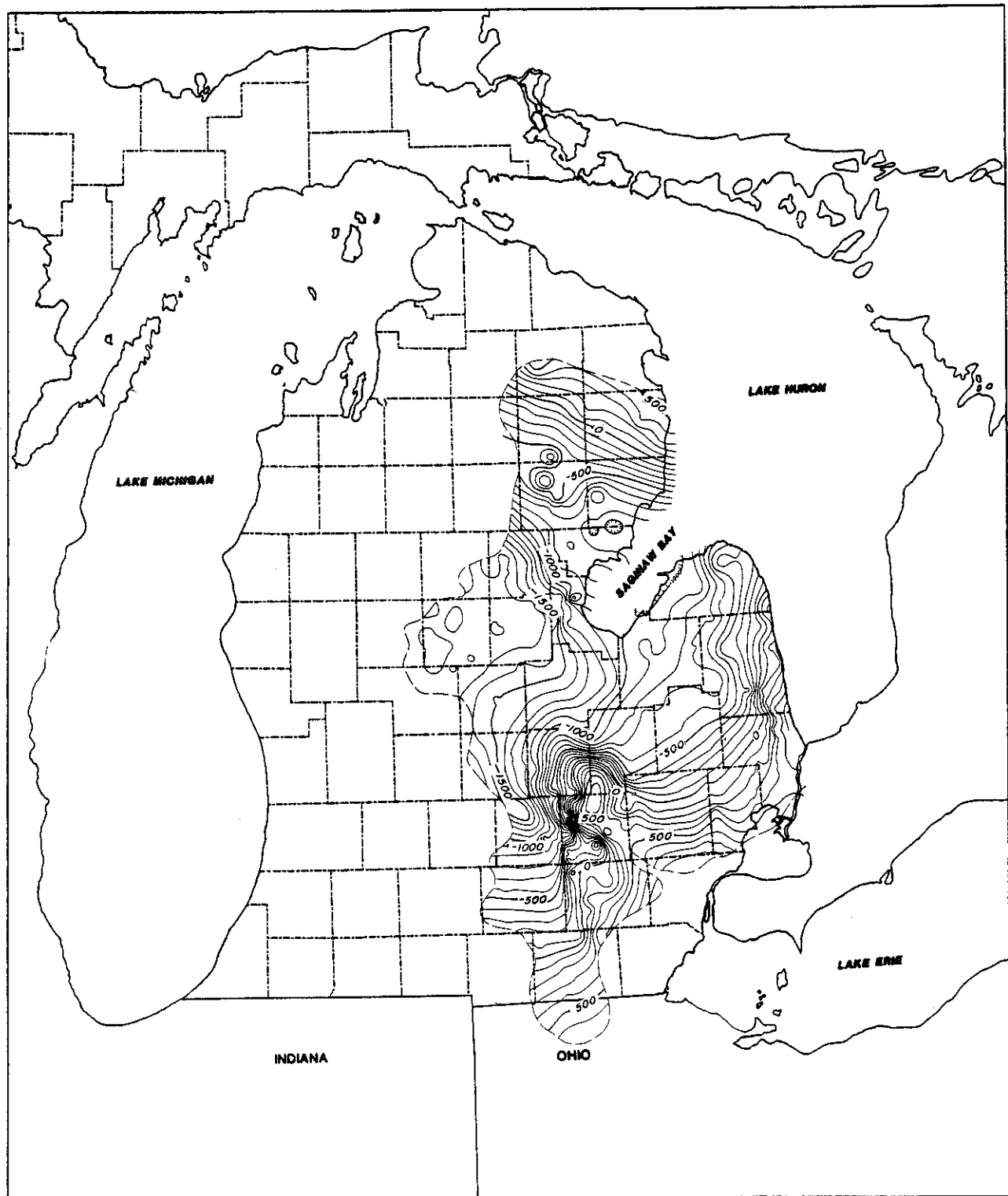


Figure 2.46. Structure map on Berea Sandstone. (From Fisher, 1980.)

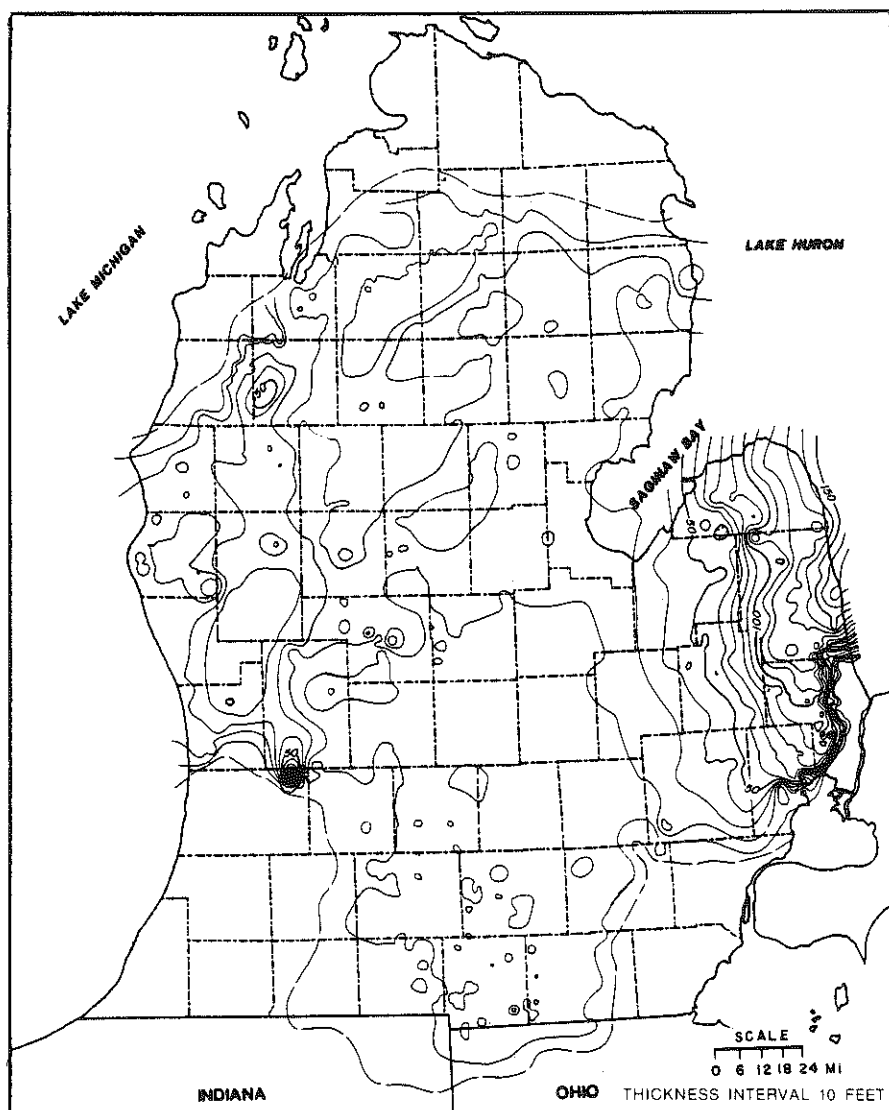


Figure 2.47. Thickness of Sunbury Shale. (From Fisher, 1980.)

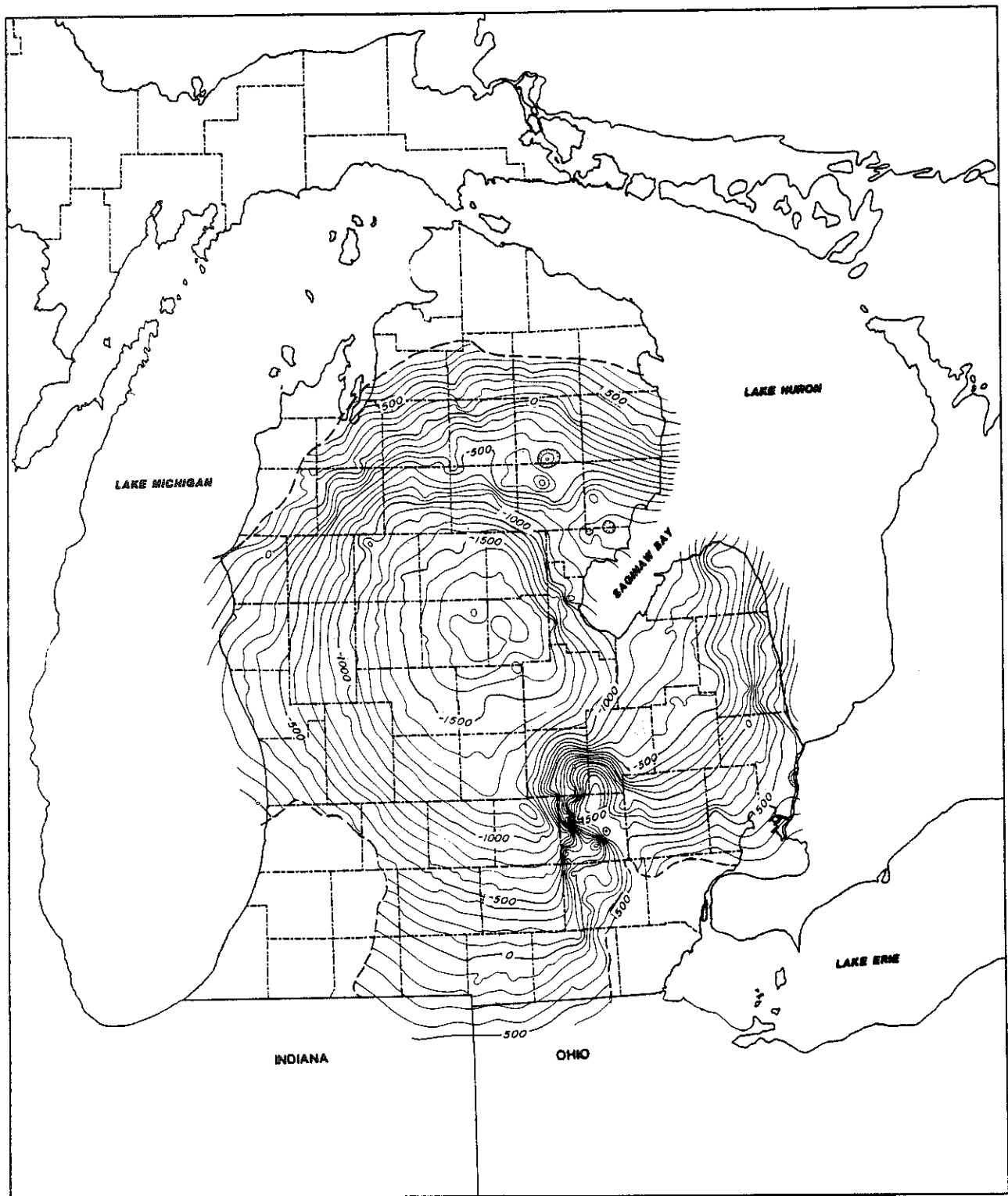


Figure 2.48. Structure map on Sunbury Shale. (From Fisher, 1980.)

Characteristics as an Aquifer. The Sunbury Shale is not an aquifer.

Characteristics as a Confining Layer. The Sunbury Shale and its western correlative, the Ellsworth, are confining layers.

Characteristics as an Injection Formation. It is far too impermeable to be used as an injection formation.

Porosity. The effective porosity of the Sunbury is very low.

Permeability. Very low.

Oil and Gas Potential. The Sunbury has limited potential as an oil shale.

MISSISSIPPIAN

Coldwater Shale

The Coldwater Shale is a gray, micaceous shale that ranges in thickness from about 500 feet in southwestern Michigan to more than 1250 feet along the eastern margin of the Southern Peninsula (figs. 2.49 and 2.50, pls. 5,6 and 12). The Coldwater is apparently a deltaic sequence with sands developed in the thick, eastern portion and limestones in the thin, western part of the formation (Lilienthal, p. 7, 1978).

Characteristics as an Aquifer. The sandstones in the Coldwater have aquifer characteristics in the area around Saginaw Bay and the "Thumb" area. The Coldwater shales are not aquifers, nor is the thin Coldwater limestone in the western Southern Peninsula.

Characteristics as a Confining Layer. The Coldwater would be an excellent confining layer except in the eastern part of the state where sandstones are present.

Characteristics as an Injection Formation. The Coldwater shale and limestone are far too impermeable to serve as injection formations. Because sandstones in the Coldwater are close to the outcrop and are used as aquifers, they should not be considered for use as injection formations.

Porosity. The sandstones in the Coldwater are coarse, with good intergranular porosity. The shales and limestones lack effective porosity.

Permeability. The Coldwater shales and limestones are relatively impermeable. The sandstones are permeable except where they contain abundant clay.

Oil and Gas Potential. The Coldwater Formation has a very low potential for the production of hydrocarbons.

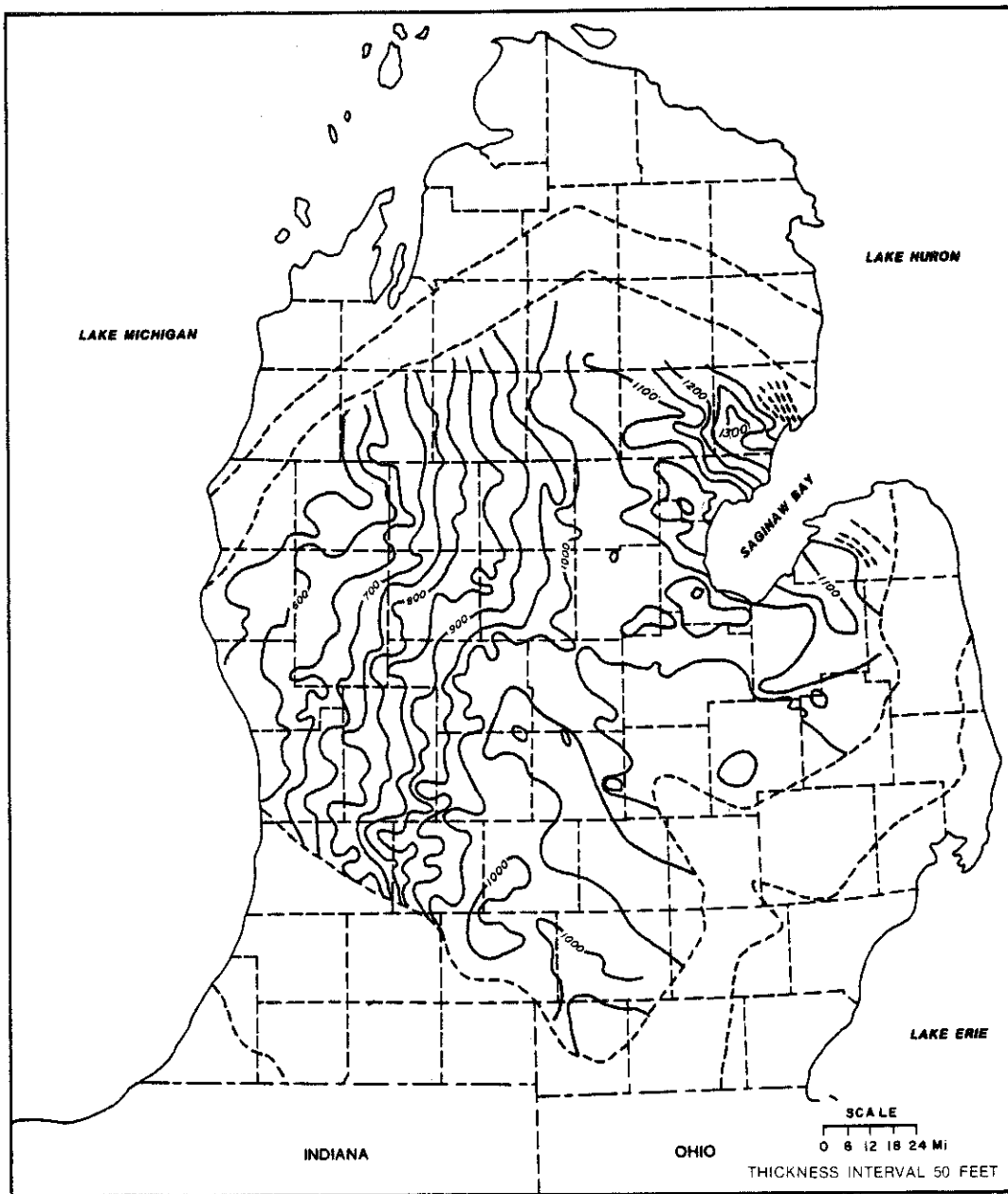


Figure 2.49. Thickness of Coldwater Formation. (From Chung, 1973.)

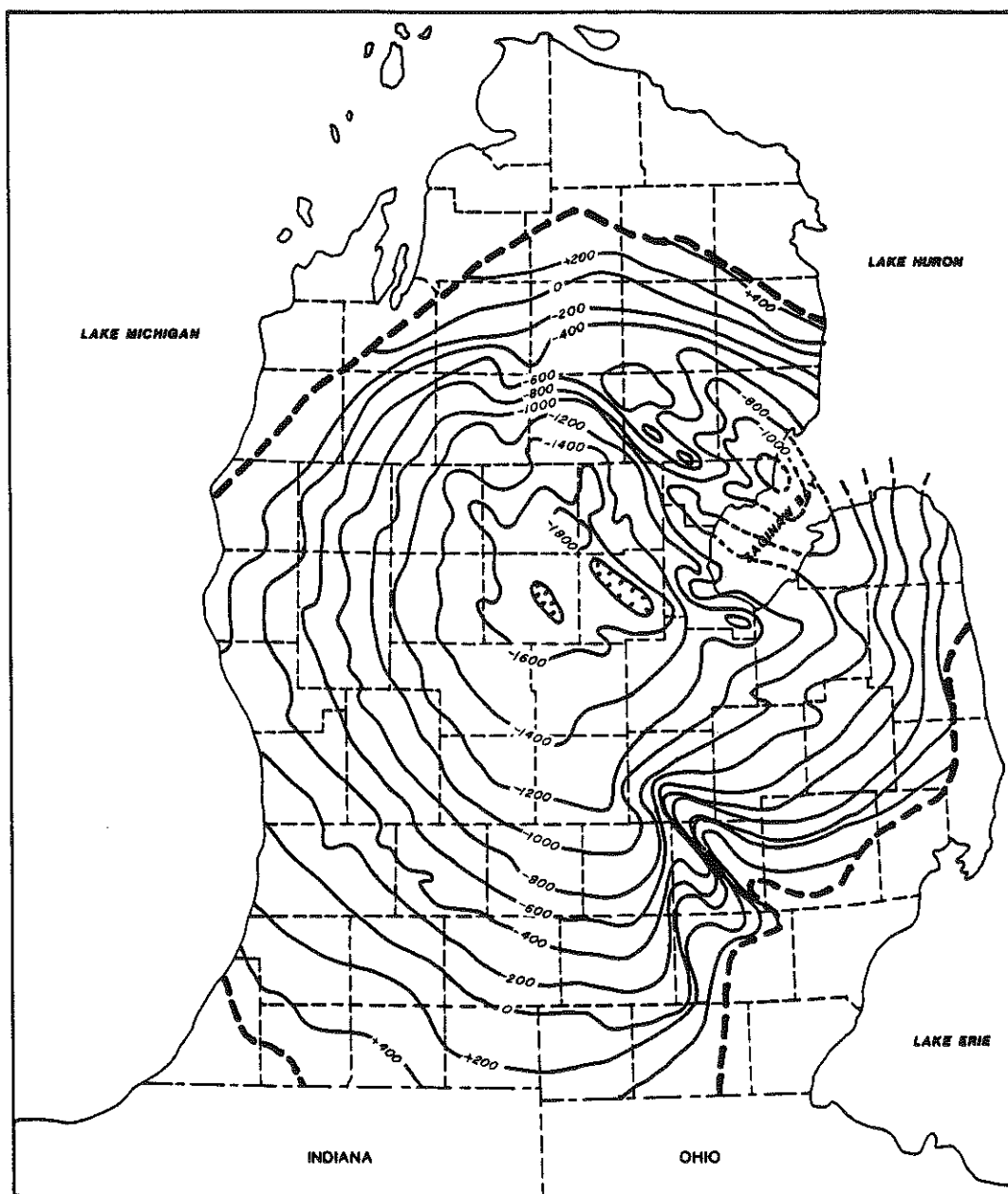


Figure 2.50. Structure contour map on the base of Coldwater Formation. (From Chung, 1973.)

Marshall Sandstone

The Marshall Sandstone is laterally equivalent to the "Stray" sandstone of the Michigan Formation (fig. 2.51). It is commonly confused with sandstones in the Upper Coldwater Formation in eastern parts of the Southern Peninsula. The Marshall comprises some 160-320 feet of sandstone, siltstone and shale. The sandstones are composed of well-sorted, fine to medium grained dominantly quartz sandstone.

Characteristics as an Aquifer. In Jackson, Hillsdale and Calhoun Counties the Marshall is considered to be a good aquifer. In Kent County and adjacent areas the water in the Marshall generally contains objectionable amounts of iron and other dissolved solids.

Characteristics as a Confining Layer. The Marshall Sandstone is too permeable to be used as a confining layer.

Characteristics as an Injection Formation. The Marshall is widely used as an aquifer and should not be used as an injection formation.

Porosity. The sandstones in the Marshall generally have good, intergranular porosity. The siltstone and shale interbeds have a much lower effective porosity.

Permeability. The Marshall sands are moderately permeable.

Oil and Gas Potential. The Marshall Sandstone is not a significant target for oil and gas exploration. Brine is produced from it in Gratiot County.

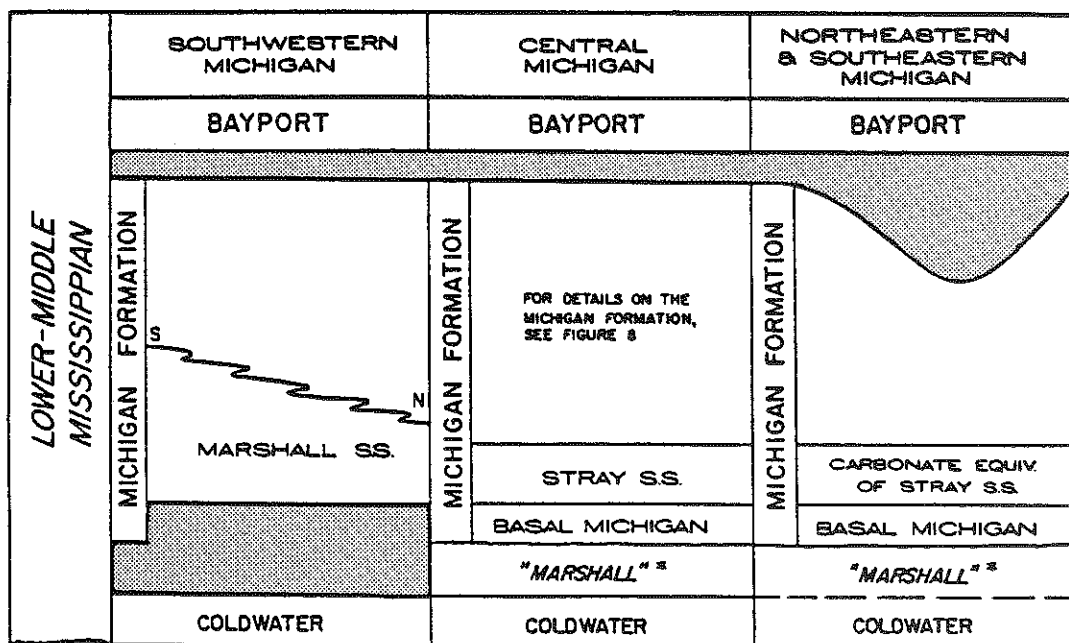
Michigan Formation

The Michigan Formation, a sequence of dark gray shale, limestone, dolomite, sandstone, gypsum and anhydrite, ranges in thickness from 0 feet at the erosional margin to more than 400 feet (fig. 2.52). The sandstones in the Lower Michigan Formation, referred to as the "Stray" sandstone, are laterally equivalent to the Marshall Formation of the northwestern Southern Peninsula (see Marshall Sandstone). The gypsum units are mined at Grand Rapids and Alabaster.

Characteristics as an Aquifer. The shale, gypsum, anhydrite and limestone units in the Michigan lack aquifer characteristics. The dolomites are slightly porous and should yield small amounts of water where they subcrop under the glacial drift. The sandstones in the Upper Michigan, sometimes referred to as the Stray "Stray", may produce water at the subcrop, but are not known to be an aquifer.

Characteristics as a Confining Layer. The shale, gypsum, and anhydrite in the Michigan have excellent characteristics as confining layers. These lithologies serve to confine gas in Stray Sand Reservoirs. The sands, dolomites and limestones should not be considered confining layers.

LOWER-MIDDLE MISSISSIPPIAN CORRELATION CHART-MICHIGAN



* THE "MARSHALL" IN THE CENTRAL AND EASTERN PARTS OF THE STATE IS OLDER AND NOT EQUIVALENT TO THE TRUE MARSHALL IN THE S.W. AND SHOULD BE RENAMED.

Figure 2.51. Lower-Middle Mississippian correlation chart-Michigan.
(Modified slightly from Moser, 1963.)

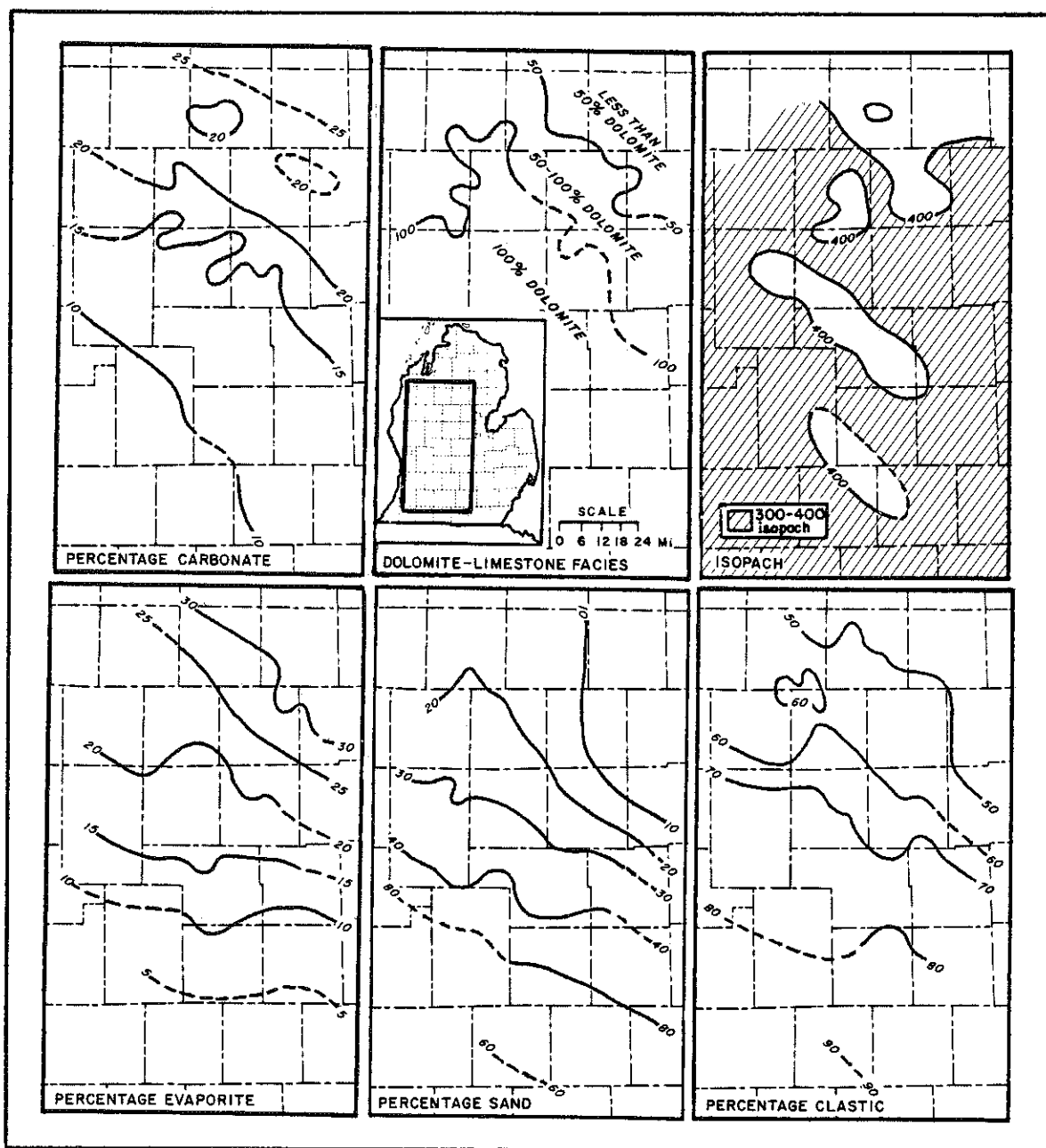


Figure 2.52. Thickness and lithofacies of the Total Michigan Formation.
(From Moser, 1963.)

Characteristics as an Injection Formation. The Stray sandstone is used as a gas storage reservoir, and would probably accept fluids in many areas. The Stray "Stray" sandstone should also be permeable enough to act as an injection formation. Other lithologies in the Michigan Formation are too impermeable to be considered injection formations.

Porosity. The effective porosity of the shales, gypsum and anhydrite is very low. The limestones are anhydritic away from the outcrop and probably have very low porosity. The fine-grained "Sugar" dolomite is probably the most porous non-sand lithology in the Michigan Formation. The Stray "Stray" sandstone is porous in southwestern Michigan. It is very likely that this unit is confused with the Marshall Sandstone by water well drillers.

Permeability. The shales, anhydrites, gypsum and limestone units in the Michigan are essentially impermeable. The "Sugar" dolomite, The "Stray" sandstone and the Stray "Stray" sandstone are all permeable in areas of thick development. Locally, these units grade into shale and are considerably less permeable.

Oil and Gas Potential. The "Stray" sandstone has produced gas in the south-central part of the basin and is being used for gas storage.

Bayport Limestone

The Bayport conformably overlies the Michigan Formation and was dissected by erosion prior to deposition of the Saginaw Formation (fig. 2.53). The basal portion of the formation is a dense, cherty, anhydritic dolomite with interbeds of quartz sandstone that range up to 10 feet thick. The middle part of the unit is fossiliferous limestone that grades upward through shaly limestone to dolomite and limestone. The Bayport ranges in thickness from 0 to more than 100 feet.

Characteristics as an Aquifer. The sandstones in the Bayport are used locally as a source of water, and the limestones are used in a few places. The local abundance of gypsum cement in the sandstones and the dense (non-porous) nature of the carbonate units precludes wide usage of this unit as an aquifer.

Characteristics as a Confining Layer. The presence of sandstone beds, some porous dolomite and dense, brittle dolomite suggest that the Bayport should not be used as a confining layer.

Characteristics as an Injection Formation. The wide range of permeabilities and the shallow depth of the Bayport indicate that it should not be used as an injection formation.

Porosity. A wide range of porosities are present in the Bayport. The sandstones and some of the dolomitic units are quite porous, but in general the limestones are not porous.

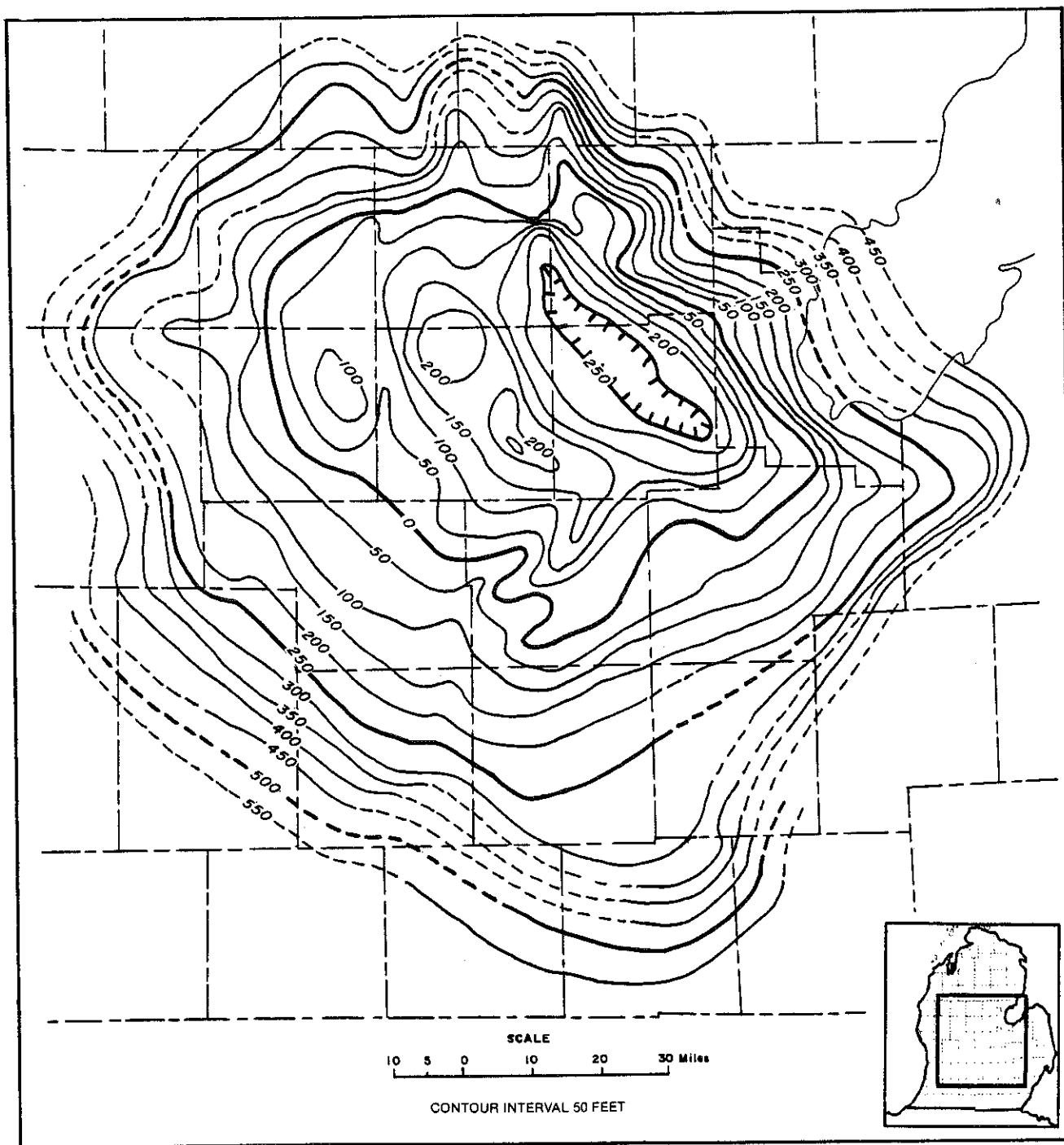


Figure 2.53. Structure contour map on base of Bayport Formation. (From Lasemi, 1975.)

Permeability. Permeabilities in the Bayport are directly correlative with rock type. The sandstones are generally more permeable than the dolomites and the limestones are relatively impermeable.

Oil and Gas Potential. The oil and gas potential of the Bayport Limestone is very low.

PENNSYLVANIAN

Saginaw

It is general practice to lump all Pennsylvania rocks in the Michigan Basin into the Saginaw Formation (fig. 2.54, pls. 5, 6 and 12). This includes lithologies previously assigned to the Parma Sandstone, Woodville Sandstone, Eaton Sandstone, Ionia Sandstone, Grand River Formation, Pennsylvanian Sandstone, and "Coal Measures". The Saginaw Formation of current usage includes a basal lenticular sandstone up to 150 feet thick and interbedded shale, coal, limestone and sandstone. The sandstones above the basal unit are irregularly bedded, generally lenticular, and although most beds are less than 10 feet thick in the central part of the state, thicknesses of more than 100 feet have been reported in some wells. The unit ranges in thickness from 0 feet at the truncated margin to 535 feet (Kelly, 1940).

Characteristics as an Aquifer. Sandstones of the Saginaw Formation are generally good aquifers with transmissibilities ranging from 9,520 gpd/ft to 37,156 gpd/ft in the Lansing area. Thick relatively clean sandstones are better aquifers than the lenticular sandstones common in parts of the Saginaw.

Characteristics as a Confining Layer. Although the shales and underclays in this unit are aquitards to aquicludes, the abrupt transition in lithologies and the presence of sandstone beds preclude use of this unit as a confining layer.

Characteristics as an Injection Formation. The sandstones in the Saginaw are aquifers and should not be used as injection formations.

Porosity. A wide range of porosities exist in the Saginaw. The lenticular, shaly sands tend to have low effective porosity whereas the thick, clean sandstone bodies have high effective porosity.

Permeability. Clean sandstone units are very permeable, but shaly sandstones have low permeability.

Oil and Gas Potential. Only one small field has been developed in the Saginaw. Its potential for oil and gas production is very low.

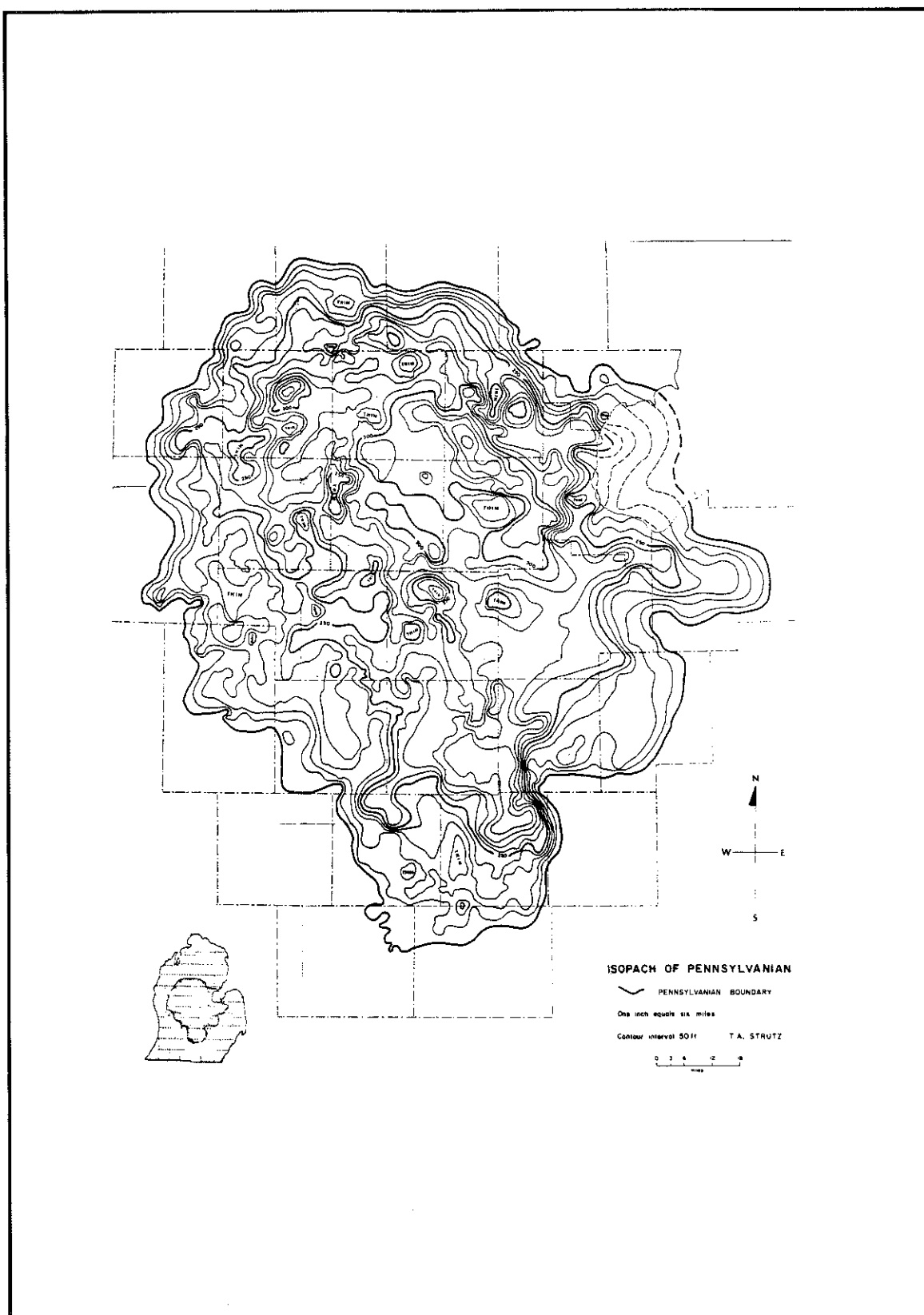


Figure 2.54. Thickness of Pennsylvanian rocks in Michigan. (From Strutz, 1978.)

JURASSIC

"Red Beds"

The "Red Beds" (pls. 5,6 and 12) are dominantly reddish-brown shale, siltstone and gypsum (Shaffer, 1969). The relative percentages of these lithologies has not been determined. The unit ranges from zero at its eroded margins to a maximum thickness of slightly over 200 feet in Mecosta County (fig. 2.55). Thickness is controlled by the irregularity of the pre- "Red Beds" topography and post-depositional erosion. The rocks are similar to materials deposited in a continental setting, and have been dated on the basis of palynology.

Characteristics as an Aquifer. The "Red Beds" are not known to be a source of water. The presence of bedded gypsum indicates that any water present would most likely be high in total dissolved solids, especially sulfate.

Characteristics as a Confining Layer. The irregular thickness and irregular margins of the "Red Beds" coupled with the presence of sandstone units preclude its use as a confining layer.

Characteristics as an Injection Zone. The irregular thickness and margins of the unit, the lack of extensive permeable units and its presence at the top of the bedrock column in the Southern Peninsula should preclude its use as an injection zone.

Porosity. Porosity is low in the gypsum beds and high in fine-grained clastics.

Permeability. Permeability corresponds closely to lithology. Gypsum beds and shale are essentially impermeable whereas the sandstones are fairly permeable.

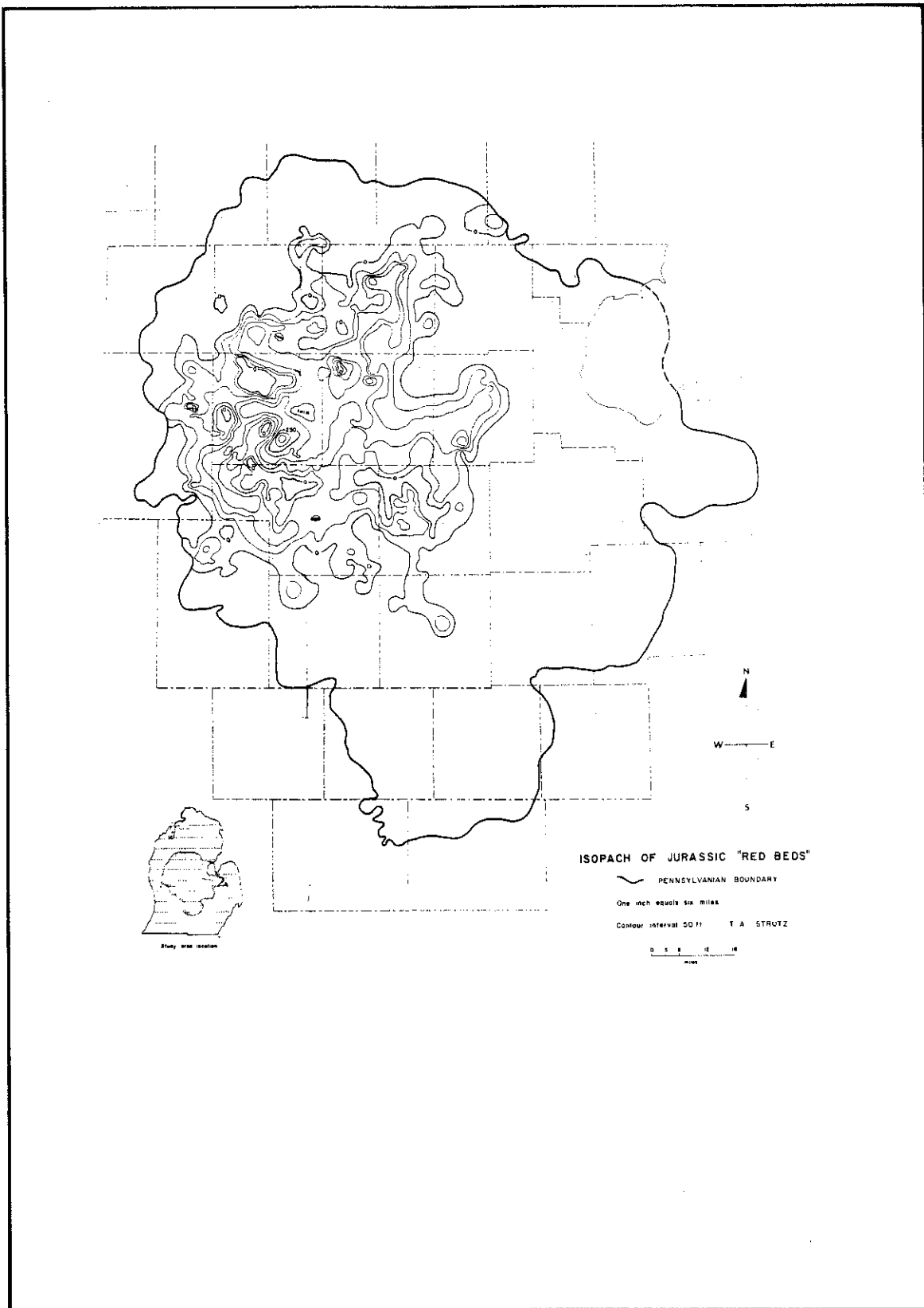


Figure 2.55. Thickness of Jurassic "Red Beds". (From Strutz, 1978.)

Geology of Glacial Deposits

GEOLOGY

Glacial History

The Pre-Pleistocene geologic history of Michigan extending back to the Jurassic Period is poorly known. It can be assumed that a pre-glacial topography (pl. 13) had formed that was similar to that in unglaciated terrain in Kentucky or unglaciated areas of Indiana. The major streams of the pre-glacial drainage system may have coincided with the long axes of the present-day Great Lake basins (fig. 2.56). This drainage system was probably controlled by the lithology and structure of the Michigan Basin with a major outlet through the south-east end of Georgian Bay to the St. Lawrence drainage.

The major valleys in this system may have developed on the soft Paleozoic shales and sandstones of the Michigan Basin parallel to strike. Such valleys could have facilitated divergence of the advancing ice front into lobes as it moved across the Great Lakes area, later to coalesce into a continuous sheet in Ohio, Indiana, and Illinois. The ice mass was thickest and moved most rapidly along the axes of the main valley depressions (Kelley and Farrand, 1967) further enlarging the depressions which were to become lake basins.

Although evidence for pre-Wisconsinan advances (Nebraskan, Kansan and Illinoian) is absent in Michigan, good evidence exists in Ohio, Indiana and Illinois. It can be surmised, therefore, that these early glaciers crossed Michigan but that evidence of their existence has been obscured by the Wisconsin advance. Additional study and subsurface investigation may someday reveal the presence of these older glacial deposits in Michigan.

As the Wisconsin glacier began to recede across Michigan, it re-established its lobate character subdividing into the Lake Michigan, Saginaw and Lake Erie lobes. During this general retreat, brief periods of equilibrium and readvance produced a series of end moraines parallel to the margins of the several lobes with some local development of interlobate moraines (fig. 2.57, pl. 14). The Sturgis moraine in St. Joseph County in southwestern Michigan, was followed by the Tekonsha moraine in Calhoun County. Further retreat of the ice margin led to the development of the Kalamazoo and Valparaiso morainic systems. With development of the latter morainic system, much meltwater was impounded behind the moraines and the first stages of the Great Lakes, Lake Chicago and Lake Maumee came into being (Kelley and Farrand, 1967). Drainage from Lake Chicago was via the Illinois River to the Mississippi and Lake Maumee via the Maumee River and Wabash River to the Ohio River. Continued retreat into the Lake Michigan basin and a subsequent readvance produced the Lake Border morainic system. In southeastern Michigan, the Erie Lobe produced the Defiance Morainic system. During the initial stages, abundant silt and clay were deposited on the lake bottoms leaving extensive lacustrine plains as the lakes receded.

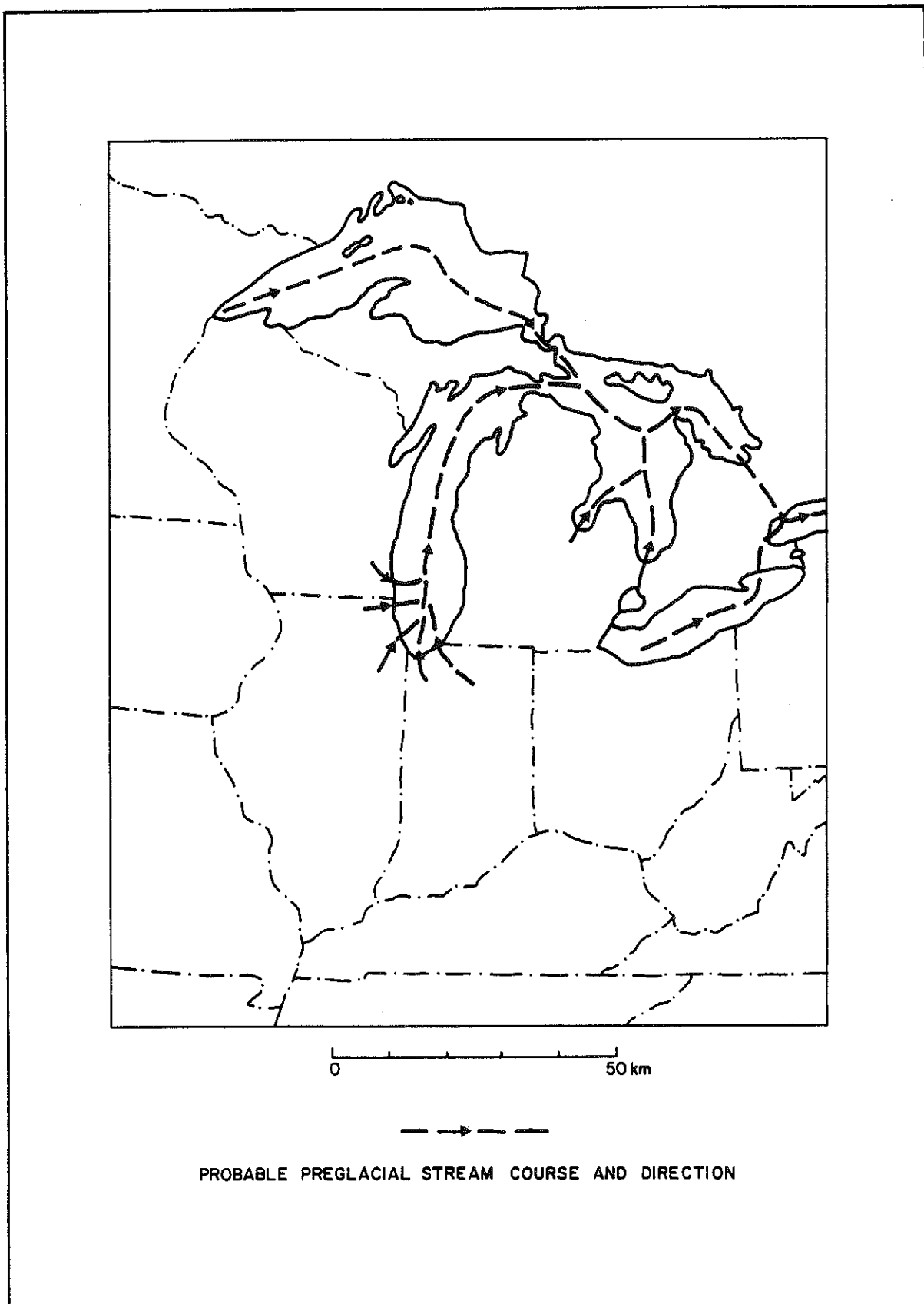


Figure 2.56. Probable preglacial river courses. (After Flint, 1971.)

Lacustrine plains are especially well-developed in southeastern Michigan in Monroe and Wayne Counties. The moraines from the Sturgis through the Lake Border systems are of Cary age ranging from 13,500 to 16,000 years before present (Dorr and Eschman, 1970).

The Port Huron morainic system represents a readvance of the Cary ice front which culminated in a well-developed terminal moraine about 13,000 years ago. The moraine parallels the margins of Lake Huron and Saginaw Bay and extends across the north-central part of the Southern Peninsula crossing Lake Michigan opposite Milwaukee. Following the Port Huron advance, there was a general retreat exposing the Straits of Mackinac and probably an extensive area of the Northern Peninsula (Dorr and Eschman, 1970). This period of ice recession, the Two Creeks interstadial, was followed by a readvance, the Valdres stadial, about 11,850 years ago. Valdres ice left deposits which extend across the northern part of the Southern Peninsula from near Muskegon on Lake Michigan to Rogers City on Lake Huron. A general retreat across the Upper Peninsula appears to have followed the Valdres advance with equilibrium conditions producing the Newberry, Marenisco, Munising, Marquette, and Covington moraines. Nearly all of Michigan was free of ice by about 10,000 years ago; however, Hughes (1978?) reported a brief subsequent readvance in the Tilden Mine area near Ishpeming.

The retreat of the glaciers left Michigan with a youthful and complex landscape, generally less than 20,000 years old developed on drift deposits ranging up to 1200 feet thick (pl. 15). The landscape is composed of low-relief features such as outwash, till and lacustrine plains and features of greater relief including end moraines, drumlins, kames, kettles, eskers, wave-cut cliffs, and dunes.

Bedrock Topography of the Southern Peninsula

In 1943 the Geological Survey Division of the Department of Conservation published a Topographic Map of the Bedrock Surface of the Southern Peninsula of Michigan (pl. 13). Based on numerous oil, gas and water well records the map shows the bedrock surface to range in elevation from -50 to 1100 ft. It reveals some striking relationships between the effect of glacial erosion and the bedrock lithology and structure of the Michigan Basin.

Western Michigan

In Berrien, Van Buren, and Allegan Counties in southwestern Michigan, the bedrock shows a radiating erosional pattern of north-south, northwest-southeast, and east-west trending valleys which extend as much as 35 miles inland from the Lake Michigan shoreline. Although trends parallel to the strike can be observed, the structural trend of the bedrock formations does not appear to have been a major controlling factor in the development of these valleys.

A large north-south trending valley extending from its terminus near South Haven to the Indiana line in Berrien County may be related to a preglacial stream valley. The bedrock topography along the western margin of the Southern Peninsula from Muskegon to the Straits of Mackinac increases in elevation inland from the Lake Michigan shoreline. In Oceana, Mason, and Newaygo Counties the elevation increases from 50 feet below sea level near Ludington to 550 feet above sea level just east of White Cloud, a distance of approximately 50 miles. The contours in this area generally parallel the strike of the Devonian and Mississippian rocks. Superimposed on this general trend are northwest-southeast trending broad valleys that appear to reflect ice scouring with diminishing effect away from the present lake margin.

In the Grand Traverse Bay area pronounced scouring also has produced a series of relatively short valleys (10-20 miles in length) with rather steep headward gradients trending north-south, transverse to the strike. This scouring has created a bedrock relief of approximately 550 feet and is likely the cause of the Grand Traverse Bay shoreline configuration and the development of Torch, Elk and Charlevoix lakes, a group of parallel inland lakes. The Little Traverse Bay bedrock valley shows an east-west trend lacking headward closure, but an opening eastward to the Lake Huron shoreline. This suggests a through flowing of the ice across this northernmost part of the Southern Peninsula.

Eastern Michigan

The northeastern part of the Southern Peninsula shows a strong strike control of the bedrock topography especially well-developed in Presque Isle, Montmorency, and Alpena Counties. This strong influence of strike is also apparent in the Thumb area and southeastern Michigan in Washtenaw, Lenawee, and Monroe Counties. No prominent transverse ice scoured valleys, with the exception of broad Saginaw Bay, are developed along the Lake Huron shoreline. Only slight valley development is present in Wayne and Macomb Counties.

A broad area of low-relief (100-200 feet) developed mostly on Pennsylvanian rocks exists west-southwest of Saginaw Bay in Midland, Isabella, Montcalm, and Gratiot Counties. The area may have been a preglacial valley system subsequently eroded by ice lobes moving out of Saginaw Bay. Some shallow closed depressions exist within the larger area.

South-Central Michigan

A general bedrock high exists in Jackson, Branch, and Hillsdale Counties. This ridge reaches elevations of 1100 feet above sea level and rises as much as 600 feet above the adjacent area in St. Joseph County. The bedrock high appears to have developed in an interlobate position between the Lake Michigan and Lake Erie lobes.

GLACIAL DRIFT THICKNESS

Southern Peninsula

Drift thickness in the Southern Peninsula of Michigan (pl. 15) ranges from zero in Alpena and Presque Isle Counties to more than 1200 feet in Wexford County. The wide range of thickness is a function of relief on the bedrock surface and the type of overlying glacial deposits. In general, the movement of glacial ice across the Southern Peninsula was controlled by bedrock features of the peninsula and adjacent lake basins. Except where they formed divides between adjacent lobes of ice, most bedrock topographic highs are associated with relatively thin drift; bedrock valleys are sites of thicker drift accumulation. Glacial lake plains are dominantly areas of thin drift, whereas moraines correspond to areas of thicker drift.

Bedrock outcrops (pl. 15) are uncommon throughout most of the Southern Peninsula. Areas of significant bedrock exposure include the northern tip of Emmet and Cheboygan Counties, northeastern Alpena County, Presque Isle County, southern Cheboygan County and Monroe County. Discontinuous exposures of bedrock occur around Saginaw Bay in Tuscola, Huron, Iosco Counties; and in south-central Michigan in Eaton, Calhoun, Jackson, Hillsdale, Branch, Lenawee, and Ingham Counties; in west-central Michigan in Ottawa and Kent Counties; and scattered locations in Ionia, Shiawassee and Genesee Counties.

A broad area extending from the northwestern margin of Saginaw Bay and the "Thumb" area southwestward to northern St. Joseph and Branch Counties and eastward to the eastern boundary of the state is mantled with drift that ranges in thickness from zero over the discontinuous bedrock exposures to as much as 400 feet, but is typified by glacial materials that are less than 100 feet thick. Glacial drift greater than 200 feet in thickness in this area is generally restricted to the interlobate moraine that formed between the Saginaw and Erie Lobes in a band that extends from southern Lapeer County southwestward to the northeastern corner of Indiana. This band of thick drift roughly coincides with an elongate bedrock high that formed the divide between these two lobes of the Wisconsin ice.

Western Michigan, with the exception of two rather small areas of thin drift in Berrien County and northern Allegan, Ottawa and southwestern Kent Counties, is covered with drift at least 200 feet thick and generally more than 400 feet thick. In Wexford County the drift is as much as 1200 feet thick. Areas of very thick drift generally coincide with interlobate deposits and materials that were deposited in areas of converging moraines. The southwestern portion of the state is characterized by irregular thicknesses of drift that generally range in thickness from 100 feet to about 400 feet. North and east of a line extending from about the northeastern corner of Ionia County to the southwestern corner of Oceana County, the glacial materials range from 200 to as much as 1200 feet in thickness and are dominantly thicker than 400 feet. The thick drift in the northern portion of the Southern

Peninsula is broken by a band of thin drift and bedrock exposure that extends from western Charlevoix County east to the lake shore in Alpena and Presque Isle Counties.

Northern Peninsula

The Glacial Drift Thickness Map of the Northern Peninsula (Plate 15, Sheet 3) was compiled from 3500 well logs and mineral exploration borings from the files of the Department of Natural Resources, Geological Survey Division, Escanaba, Michigan. Areas of bedrock at or near the surface are mapped as shown on the Surface Formations of the Northern Peninsula of Michigan (Martin, 1957). The accuracy of drift thickness is dependent upon the density of data points which reflects mining development and/or population concentration. Where mining activity and population growth have not occurred, large areas of the map are labeled "Insufficient Data". Such areas are most conspicuous in Gogebic, Ontonagon, Iron, and Houghton Counties in the western Northern Peninsula and Schoolcraft, Luce and Chippewa Counties in the eastern Northern Peninsula.

Drift thickness in the western Northern Peninsula is highly variable corresponding to glacial deposits and bedrock topography. Areas of thickest drift in the western Northern Peninsula coincide with areas of end moraine. Relief on the bedrock surface differs greatly as a function of the bedrock resistance of Precambrian rocks and also significantly influences drift thickness. A large area of drift covering parts of Menominee, Delta and Alger Counties ranges from 11 to 50 feet in thickness with isolated regions from 101 to 200 feet. This region extends from the Wisconsin border to Lake Superior and is mapped as ground moraine, till plain, and outwash.

In the eastern Northern Peninsula, sufficient data exist only for an area adjacent to the Lake Michigan shoreline extending from Delta County to Chippewa County, including central and northern Chippewa County. Drift thickness in this area varies greatly from over 200 feet to negligible thicknesses over exposed bedrock. The drift is mapped as ground moraine, till plain, and outwash sediments with dune and beach deposits. Areas of thickest drift occur in easternmost Chippewa County and in part correspond with bedrock valleys and end moraine deposits.

Other Geologic Factors

GEOLOGIC STRUCTURE

Michigan lies within the Lake Superior, Penokean and Central Provinces of the Precambrian Shield of North America, provinces which are defined on the basis of structural trends, structural deformity, and age dates (fig. 2.58). The most prominent structural feature within the state is the Michigan Basin centered on the Midland County area of the Southern Peninsula and extending outward to Georgian Bay and Ontario on the east; Ohio, Indiana and Illinois on the south; and Wisconsin on the west (fig. 2.58, pls. 4 and 16). The basin is bounded structurally on the east by the Algonquin Arch, on the southeast by the Findlay Arch, on the southwest by the Kankakee Arch, on the west by the Wisconsin Arch and Dome and on the north by the Canadian Shield (pl. 4). The contact of the northern erosional edge of the Basin's Paleozoic sediments and the Precambrian rocks may be close to the tectonic limit of the Basin across the Northern Peninsula (Michigan Basin Geological Society, 1969).

From Menominee to Marquette in the Northern Peninsula, Middle Precambrian metasediments of the Penokean Province are generally folded into predominantly east-west trending, westwardly plunging basins or troughs that include the Marquette Synclinorium, the Republic Trough, the Felch Trough, the Calumet Trough, and the Menominee Trough (fig. 2.59, pl. 6). Further west along the northwest side of the Keweenaw Peninsula, a sequence of Precambrian Y sedimentary rocks dip northwesterly into the Lake Superior Syncline. These rocks are truncated to the southeast by the northwest-trending Keweenaw Fault which bisects the Keweenaw Peninsula longitudinally and places them in juxtaposition to the Precambrian Z Jacobsville Sandstone. The Precambrian rocks of the western Northern Peninsula are cut by numerous complex fracture systems of less magnitude (pl. 16).

It has been theorized that the origin of the Michigan Basin is related to the Keweenaw Fault (Newcombe, 1933). The dominant Paleozoic structural trend of the Michigan Basin is northwest-southeast and may be controlled by folding or zones of structural weakness in the basement. Hinze and Merritt (1971) concluded that the northwesterly intra-basin structural trend reflects weakness in the basement associated with the Mid-Michigan Rift zone and that rejuvenation of movement along this zone, together with basement surface relief, are the primary causes of basin structures. Other possible causes of deformation include rotational shear due to faulting of the Precambrian basement, differential compaction over buried topographic highs and reefs, and solution of soluble rocks (Ells, 1969). Draping and thinning of Silurian to Mississippian strata over Silurian reefs is relatively common in Michigan.

Prouty (1971) compiled the major fault traces and anticlinal fold axes from the Silurian through the Mississippian on a map of the Basin (pl. 16). Devonian and Mississippian folds are principally oriented northwest-southeast in the eastern, southeastern, and central portions of the basin (Ells,

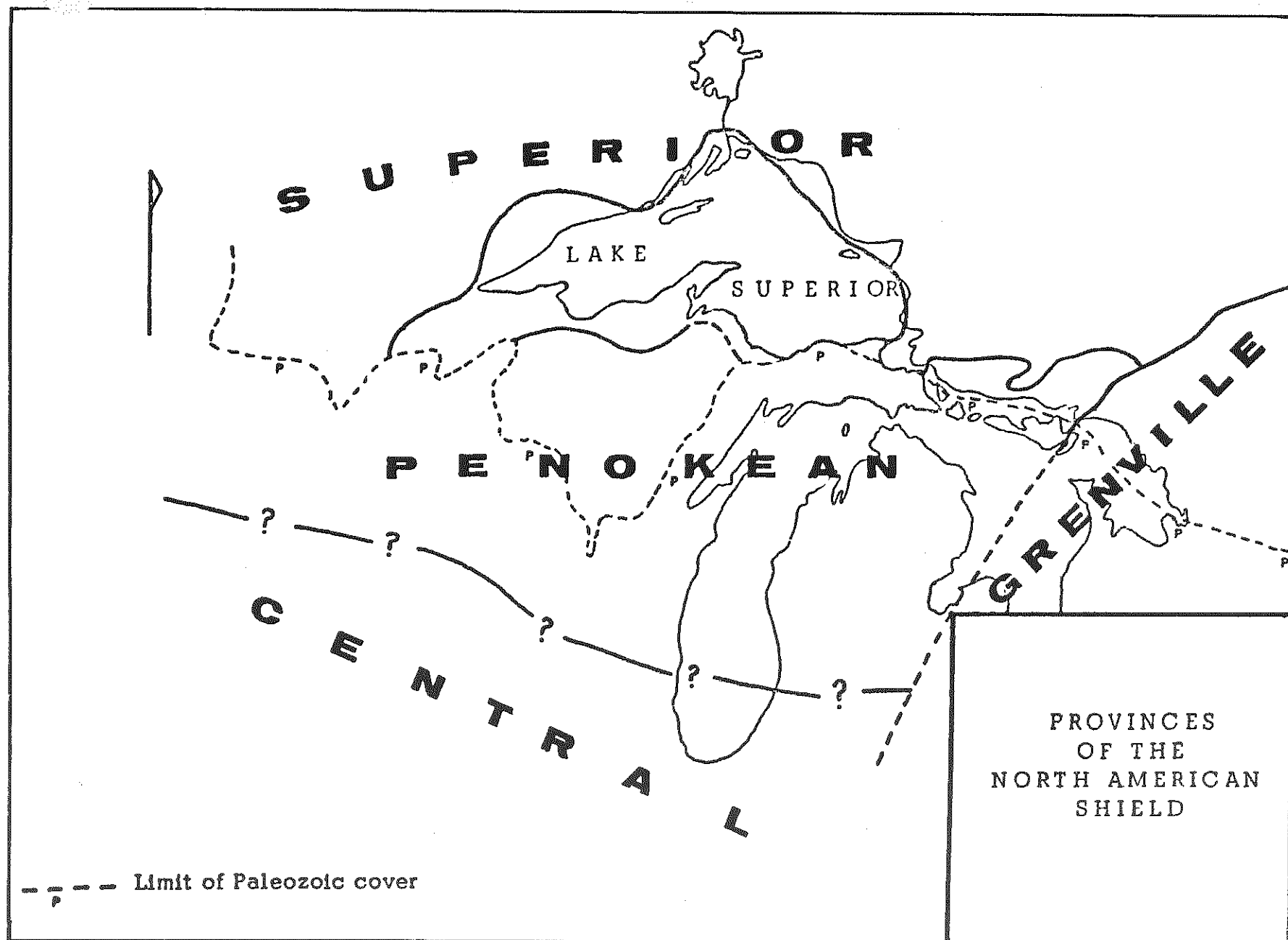


Figure 2.58. Geologic provinces of the North American Shield.

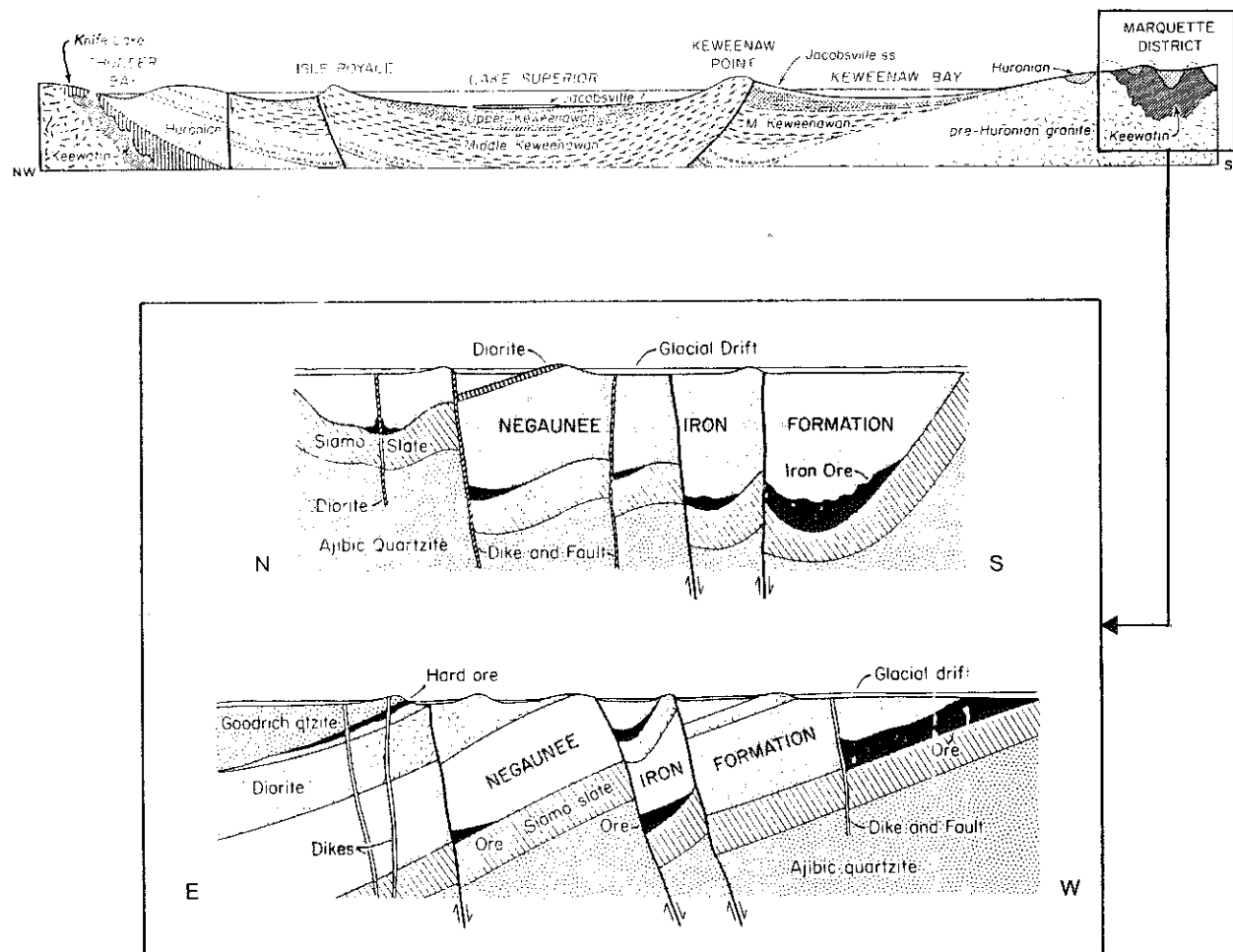


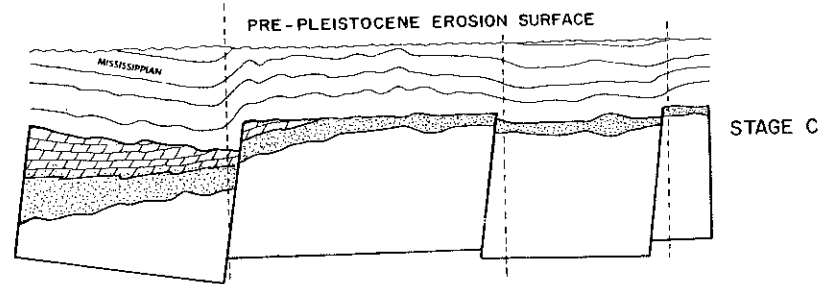
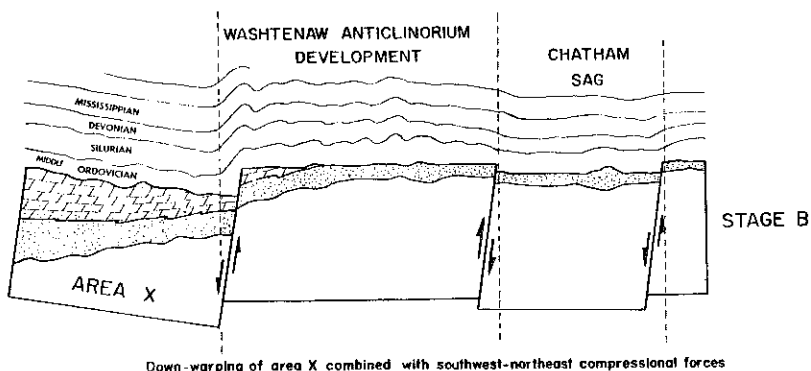
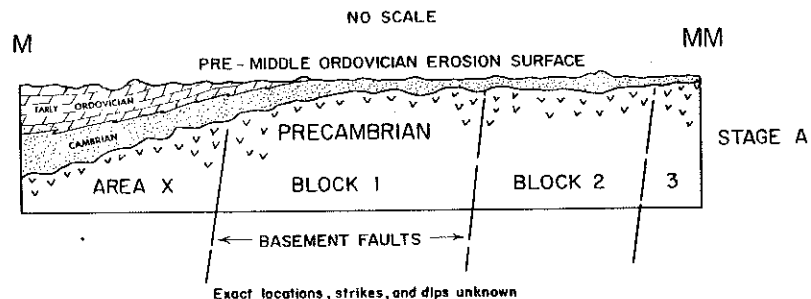
Figure 2.59. Generalized geologic cross section through Lake Superior, Keweenaw Peninsula, and detailed cross sections through the Marquette Iron Range. (From Dorr and Eschman, 1970.)

1969). North-south flexures are found in the southern and north-central parts of the basin. With the exception of those within the Washtenaw Anticlinorium (fig. 2.60) of southeast Michigan, salt-related structures of southwest Michigan, and certain areas of Upper Silurian reef development, data are generally insufficient to determine whether structures persist downward into pre-Devonian strata (Ells, 1969). The Washtenaw Anticlinorium is a broad anticlinal feature covering approximately 4500 square miles in southeast Michigan. It contains a series of sub-parallel small anticlines including the Clinton, Freedom, Unadilla, Howell, and Northville anticlines and the Lucas Monocline. The Howell Anticline is the most prominent of several northwesterly plunging structures in the Washtenaw Anticlinorium. Extending northwestward from Livingston County into Clinton County, it has been interpreted as a series of linear, somewhat offset, very asymmetrical anticlines with more than 400 feet of structural closure on the Middle Ordovician Trenton Group. These structures may be forced folds over an en echelon fault system in Precambrian basement rocks.

As with fold axes, most fractures within the Michigan Basin have a northwest-southeast orientation; others trend northeast-southwest (Ells, 1969). Several oil discoveries have been made in dolomitized fractures within fault zones such as the northwest-trending Albion-Scipio field in south-central Michigan. The Ordovician Trenton-Black River field extends for more than 35 miles through Hillsdale, Jackson and Calhoun Counties but averages less than one mile in width (Hinze and Meritt, 1969). It has been suggested that this linear fracture zone is controlled by slight lateral movement along a basement fault, possibly reflected in regional gravity anomaly trends related to topographic relief on the basement along a fault or fault-line scarp (Merritt, 1968). The northwest-oriented, en echelon folds in Midland and Isabella Counties have also been related to movements along basement faults. Structures within the Washtenaw Anticlinorium of southeast Michigan apparently persist into pre-Devonian rocks. In contrast, salt-related structures in southwest Michigan, and draping associated with Silurian reefs is not known to extend below Middle Silurian strata. Elsewhere, data are generally insufficient to determine if structures persist below Devonian rocks. The northern boundary of the Washtenaw Anticlinorium marks a change in the structural patterns in the Devonian Dundee Limestone and the northward disappearance of pronounced Dundee structural highs. Additional faulting within the Washtenaw Anticlinorium is evidenced by the absence of salts, and severe brecciation of the salt-bearing interval over the Howell Anticline suggests minor faulting on the west flank of the structure and across the southern end of the structure (Ells, 1969).

The North Adams, Deep River, and Pinconning oil fields in Arenac and Bay Counties are apparently dolomitized zones developed along a conjugate shear system (fig. 2.61). In support of this hypothesis, wells in the Pinconning field cored sheared Dundee Limestone.

DEVELOPMENT OF WASHTENAW ANTICLINORIUM



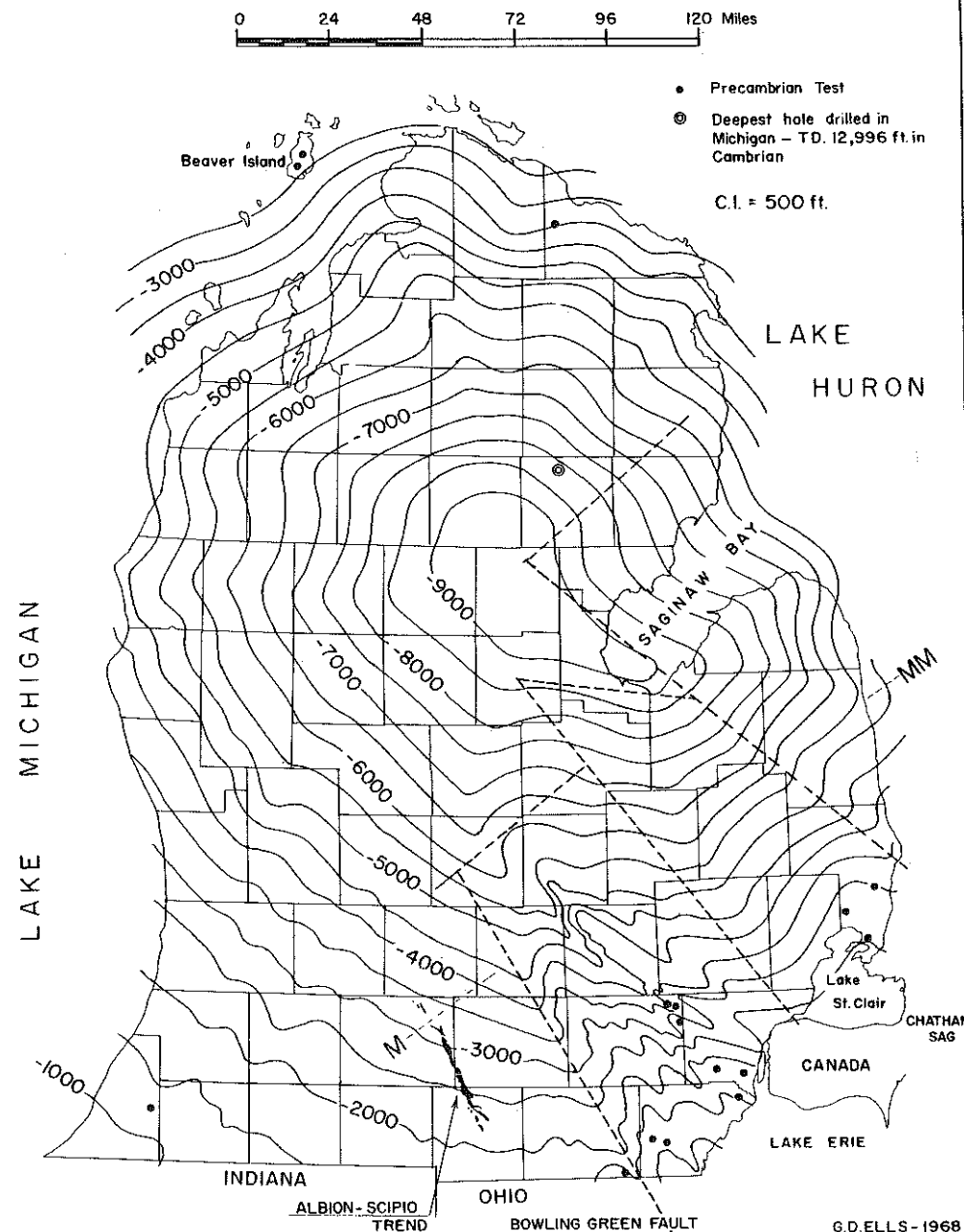
Refer to Cobbe (1945), Chart 9, Lower Ordovician and Cambrian rocks in the Michigan basin, for distribution of Lower Ordovician and older rocks beneath rocks of Middle Ordovician age. Also, Cobbe (1946), Chart 11, for thickness of Trenton-Black River rocks and contours on base of Trenton-Black River limestone in the Michigan basin.

The number of wells drilled into Trenton-Black River or deeper rocks west of the western edge of Block 1 is in the order of 3 to 4 times the number found in the area covered by Blocks 2 and 3. Yet, west of the Washtenaw Anticlinorium, subsurface data reveals no structure of the magnitude found on the Anticlinorium. The Trenton-Black River anticline

structure found in this region are of low relief, having but a few tens of feet closure and trending northwest-southeast.

The Albion-Scioto Trend, located in this structurally undeveloped region, produces oil and gas from a connected system of shallow, dolomitized synclines associated with low relief anticlines. The lineation of the main trend and the nature of the narrow dolomitized spurs which connect with it suggest a shear zone probably related to slight lateral movement along a basement fault.

CONTOURS ON THE TOP OF THE TRENTON GROUP



G.D. ELLS - 1968

F. 2.60. Structure contours on the top of the Trenton Group and development of the Washtenaw Anticlinorium. (From Michigan Basin Studies of Precambrian.)

group and development of the Washtenaw Anticlinorium.



Figure 2.61. Fault related oil and gas fields. (From Brickner, 1977.)

KARST

Known karst in Michigan is present in carbonate and evaporite rocks deposited during the following periods: Ordovician Black River, Trenton and Richmond Groups; Silurian Cataract, Burnt Bluff, Manistique, Niagaran and Salina Groups; Devonian Bois Blanc Formation, Detroit River and Traverse Groups; and Mississippian Grand Rapids Group (pls. 6,7, and 18). Significant evidence of dissolution is generally confined to the area of outcrop or subcrop under the glacial drift and to one or more carbonate or evaporite units within each of these groups (table 2.2).

Ordovician

Karst features in Ordovician rocks are common throughout carbonate and evaporite strata in the Northern Peninsula, and are generally limited to the area where the formations subcrop beneath the glacial drift. Solutional activity occurs in Ordovician strata as enlarged fractures and widening along bedding planes in near-surface rocks. Most solution is thought to have occurred before glaciation when the rocks were exposed at the surface, and is generally confined to areas where the carbonates are not overlain and thereby protected by younger rocks (Vanlier and Deutsch, 1958). The yield of water from Ordovician carbonates in the Northern Peninsula is dependent upon the extent of the solutionally enlarged permeability, and decreases where soluble rocks are overlain by other strata. Bacterial contamination of karst aquifers is a serious problem because hydraulic continuity between the glacial drift and the fractured carbonate strata allows rapid movement of contaminated wastes from the overlying drift.

Silurian

Karst features in Northern Peninsula Silurian strata are generally restricted to solutionally-widened crevices and fractures along bedding planes, and to zones where interbedded lenses of evaporites, notably gypsum, have been dissolved. In the eastern Northern Peninsula evidence of solution of Early Silurian carbonates exists near Big Spring (T 42N, R 17W, Sec. 26), Schoolcraft County, where several sinkholes filled with glacial sediment have been located. These sinkholes, including Big Spring, are assumed to have been formed through dissolution of limestone or gypsum beds in the Burnt Bluff or Cataract Groups (Poindexter, 1935). Other evidence of karst activity in Northern Peninsula Silurian carbonate rocks includes sinks, a swallow hole, a subterranean stream and a karst spring in Trout Lake Township (T 44N, R 5W, Secs. 22 and 27), Chippewa County and a feature thought to be a sink in Detour Township (T 42N, R 3E, Sec. 4), Chippewa County.

Solution features in Southern Peninsula Silurian strata are generally restricted to the Bass Island Group in southeastern Michigan, and are solutionally-widened crevices and fractures along bedding planes and zones where evaporite stringers have been dissolved.

TABLE 2.2 - OCCURRENCE OF SOLUTION FEATURES IN MICHIGAN.

PERIOD	ROCK UNIT	COUNTIES
Mississippian	Michigan Formation	Kent, Iosco
Devonian	Traverse Group	Alpena, Charlevoix, Montmorency, Presque Isle
	Alpena Limestone	
	Newton Creek Limestone	
	Genshaw Formation	
	Ferron Point Formation	
	Rock Quarry Limestone	
II-117	Mackinac Breccia	Alpena, Antrim, Charlevoix, Cheboygan, Emmet, Leelanau,
	Detroit River Group	Mackinac, Presque Isle
	Bois Blanc Formation	
	Garden Island Formation	
	St. Ignace Dolomite	
	Dundee Limestone	Alpena, Cheboygan, Emmet, Monroe, Presque Isle
	Detroit River Group	Alpena, Cheboygan, Emmet, Monroe, Presque Isle
Silurian	Salina Group	Chippewa, Delta, Mackinac, Schoolcraft
	Engadine Dolomite	
	Burnt Bluff Group	Schoolcraft, Delta, Mackinac
	Cataract Group	
Ordovician	Richmond Group	Delta, Chippewa, Luce, Menominee, Schoolcraft
	Trenton Group	
	Black River Group	

Devonian

Widespread karst development in Michigan occurs in carbonate rocks of Devonian age. Karst features have been identified in carbonates of the Devonian Detroit River, Dundee Limestone and Traverse Group rocks in southeastern Michigan. Ground-water flow has caused and is now causing solution channels to be formed in the Detroit River dolomites. Shallow sinkholes have been identified in several locations in Whiteford Township (T 6S, R 8E) (Moses, 1977, and Mozola, 1969).

Karst features in Devonian are generally restricted to solutionally-widened fractures along bedding planes and solutionally-enlarged crevices. They are most pronounced in the area where the formation outcrops or subcrops beneath the glacial drift, and are not as evident where the rocks are overlain by other rock units.

Michigan's most prominent karst development occurs in Alpena and Presque Isle Counties where Traverse Group limestones are highly fractured at the subcrop and outcrop (Kimmel, 1973). These fractures are principal factors promoting solutional activity in this area. Bedding surfaces in the thinly layered Ferron Point and Genshaw formations provide pathways for circulating ground water and thereby promote solutional activity (Ehlers and Kesling, 1970). The karst features are most evident at the surface in Alpena and Presque Isle Counties where they are thinly covered by glacial deposits. Apparently a large amount of preglacial dissolution took place over the length of the Traverse Group subcrop. The evidence of similar solutional features is probably present in the northwestern portion of the Southern Peninsula but is hidden by thick deposits of glacial materials (Smith, 1966).

The active dissolution of the Traverse Group carbonate rocks has a large bearing on the quality and availability of ground water in Alpena and Presque Isle Counties, and is a key factor in the concern for protection of the domestic drinking water supplies in the northeastern Southern Peninsula. Most of the domestic wells and some municipal wells draw water from limestone units in carbonate rocks of the Traverse Group. Only a thin layer of glacial drift overlies the limestones in much of eastern Presque Isle and Alpena Counties. Consequently a very limited amount of renovation of liquid wastes can occur before the waste liquid reaches the ground water through the highly fractured bedrock. A hepatitis outbreak in Posen, Presque Isle County, was traced to the septic tank effluent contamination of domestic wells completed in fractured limestone (Johnson, 1960; Vogt, 1961). The situation was intensified by drawdown of the water levels in the limestone by domestic wells. Also, the numerous sinkholes in Alpena and Presque Isle Counties are potential pathways for the introduction of contaminants into the drinking-water supplies. In Maple Ridge Township (T 32N, R 7E) a sinkhole has been used for the Cathro Dump. The operation was closed by the Department of Natural Resources, and its effect on the ground water in the area remains undocumented.

Mississippian

Solution activity has occurred in the Mississippian Michigan Formation and is expressed at the surface near the City of Grand Rapids, Kent County, and in southwest Iosco County. The karst features are formed by the dissolution of gypsum beds in the Michigan Formation (Moses, 1977). Several sinkholes and the Pellerito Cave are located just east of Grand Rapids (T 7N, R 12W), Kent County. Solution valleys and several sinkholes are also located in Burbright Township (T 21N, R 5E, Sec. 32), Iosco County.

MINING

Drainage from active and inactive mines may cause physical and/or chemical pollution of surface and ground water from natural drainage, pumping and surface runoff. Underground mining normally causes only minor physical pollution of surface water resulting from surface dumps and waste and tailing piles. Chemical pollution occurs through leaching of soluble minerals or through oxidation of ore and gangue minerals.

Copper

Although copper was mined in the Northern Peninsula of Michigan by pre-settlement indigent peoples, modern mining began in 1845 with formation of the Copper Falls Company (Gere, 1979 and Leskinen, 1980). About 110 mines were opened between 1845 and 1925, but few were financially successful (pl. 17).

Copper occurs in Michigan as native copper and chalcocite in amygdaloidal basalts, conglomerates and veins of fissure lodes in rocks of the Late Precambrian Keweenaw Series. Native copper occurs in flows and inter-flow conglomerates of the Portage Lake Lava Series; copper sulfides occur with minor native copper at the base of the Nonesuch Shale (White, 1971). The Keweenaw Portage Lake Lava Series and Nonesuch Shale extend from the northern tip of the Keweenaw Peninsula southwest through the Porcupine Mountains into Wisconsin (Dorr and Eschman, 1970) (fig. 2.1). Of the 12,981,204,784 pounds of copper produced through 1977, 96.5 percent was native copper, and 1.93 percent was from fissure lodes (fig. 2.62, table 2.3). At least 36 mines were in operation during the post-1926 period (Leskinen, 1980), however only the White Pine Mine was in operation as of 1979 (fig. 2.63).

The White Pine Copper Company mine is located six miles south of Lake Superior on land adjacent of the Porcupine Mountains Wilderness State Park. Untreated water from Lake Superior used in the mill, smelter, and fire refinery is discharged into a retention basin which provides clarification and conditioning of industrial point and non-point water sources before the water is piped through a series of secondary settling ponds. Discharge from the secondary settling ponds is into Perch Creek and finally into the Mineral River (White, 1971). The company has pollution control, land reclamation, wildlife management, and scientific forestry programs (White, 1971).

Water accumulates in underground workings from precipitation, percolating ground water, residual mineralizing fluids trapped in the rock, and water pumped to the mine for drilling purposes and dust control. Such water must be continuously pumped from the mine to a tailings basin, diluted and discharged. Prior to 1973 water from the mine workings was pumped to the surface and discharged into the natural drainage system. Because NPDES permits were required after 1973, mine water was confined in a drainage basin for most of the year.

TABLE 2.4 - REFINED COPPER PRODUCTION (POUNDS) FROM ALL LODES.

(Source: Copper County History by Christine & Laurie Leskinen, 1980)

	1845-1925	1926-1977	LODE TOTAL	% OF NATIVE COPPER LODES
Algoma amygdaloid	12,467	112,368 ^b	124,835	
Allouez conglomerate	69,521,253	4,454,284 ^b	73,975,537	
Arcadian amygdaloid	4,783,711	22,430	4,806,141	
New Arcadian amygdaloid	164,794	0 ^b	164,794	
Ashbed (+Atlantic) amygdaloid	142,840,804	6,219,555 ^b	149,060,359	1.42
Baltic (+Superior) amygdaloid	873,525,912	427,942,546	1,301,468,458	12.37
Calico amygdaloid	8,006,420 ^b	0 ^b	8,006,420	
Calumet and Hecla conglomerate	3,375,361,468 ^b	843,173,416 ^b	4,218,534,884	40.08
Evergreen series	66,508,152	5,565,470	72,073,622	
Houghton cgl. & Iroquois amyg.	0	86,022,420	86,022,420	
Isle Royale amygdaloid	210,839,585	130,550,073 ^b	341,389,658	3.24
Kearsarge amygdaloid	1,176,948,378	1,094,869,382 ^b	2,271,817,760	21.58
Kingston conglomerate	0	19,959,554	19,959,554	
Lake amygdaloid	7,326,227	0	7,326,227	
"Mesnard" epidote	84,095	0 ^b	84,095	
Nonesuch	18,622,725	2,455,666,905 ^b	2,474,289,630	
Csceola amygdaloid	416,398,662	179,713,337 ^b	596,111,999	5.66
Pewabic amygdaloid	873,712,184	206,916,809 ^b	1,080,628,993	10.27
Fissures ^a	199,853,050	3,487,180	203,340,230	1.93
Not designated	71,015,685	24,858	71,040,543	
Mines on Isle Royale	978,625	0	978,625	
TOTALS	7,516,504,197	5,464,700,587	12,981,204,784	
		Native Cu	10,525,378,879	96.50

^aIncludes 230,897 pounds mohawkite from Mohawk Mine^bIncludes reclamation of sands and slimes

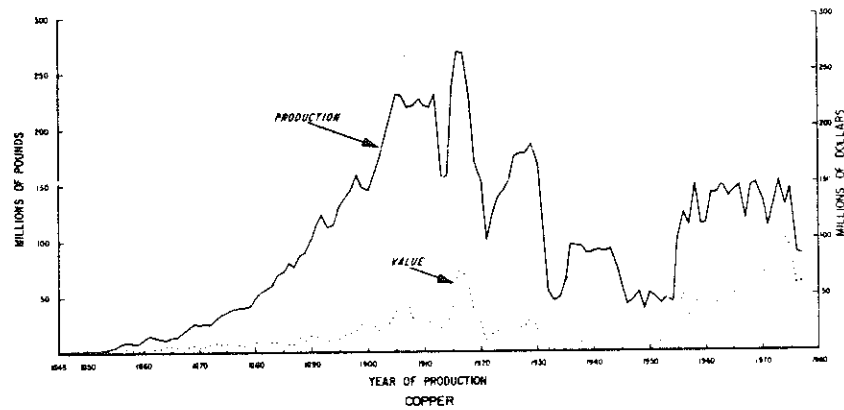


Figure 2.62. Production and value of Michigan copper 1845-1977.

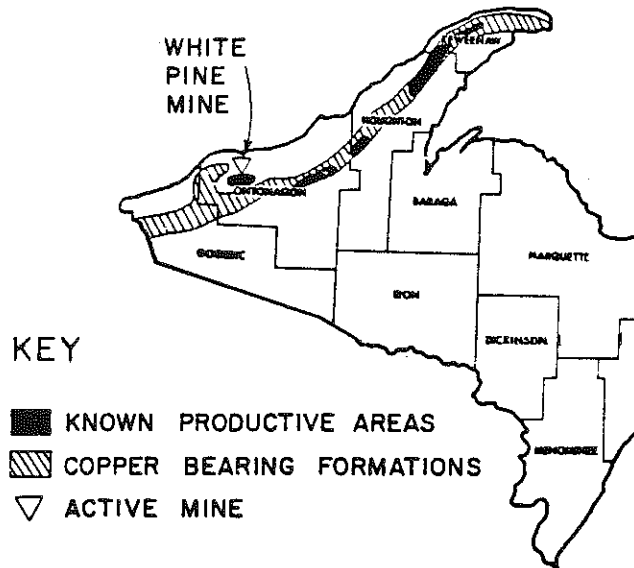


Figure 2.63. Michigan copper resources.

Numerous tailing piles are located on the Keweenaw Peninsula along the shorelines of Lake Superior, the Keweenaw Waterway and Torch Lake. Torch Lake was used as a deposition basin for copper mining water from stamping mills. Amygdaloid waste rock was deposited in the lake after the copper was extracted.

Iron

Although bog iron ore was mined in the vicinity of Union City as early as 1836, extensive iron ore mining began with the first iron ore discovery in the Marquette Iron Range in 1844 (Reed, 1975) (fig. 2.64 and 2.65). It was followed by discoveries in the Menominee Range in 1848 and the Gogebic Range in 1883. Production figures for 104 mines in the Marquette Range (pl.17) show a gradual increase from 3000 tons in 1954 to a maximum of 13,361,958 long tons in 1976 (table 2.4). Production from 85 mines in the Menominee Range increased from 10,405 tons in 1877 to a maximum of 6,428,149 tons in 1920. Production in 1977 was 2,332,305 long tons. Production figures from 17 mines in the Gogebic Range show an increase from 1,022 tons in 1884 to a maximum of 7,956,459 in 1920, decreasing thereafter to 238,851 long tons in 1967 when production ceased. Michigan ranked second in the nation in iron ore production for 1977 having produced over 1 billion long tons since 1854. As of 1978 there were 4 open pit and 2 underground mines active in the state, 4 in the Marquette Range and 2 in the Menominee Range. The Sherwood Mine closed in July of 1979 ending production from the Iron River-Crystal Falls area and Michigan's history of direct shipping iron ore (without beneficiation).

The Iron River valley consisting of Mineral Hills, Iron River, Stambaugh, Caspian and Gastra was a major underground iron mining area. Surface subsidence into underground workings and acid drainage waters from flooded mines and surface mine dumps by past mining activities resulted in pollution of the Iron and Brule Rivers (WUPDR, 1978) and acid drainage into the Iron River has caused discoloration by iron hydroxide precipitate. The acid waters are high in dissolved sulfate, iron, calcium, magnesium, manganese and aluminum. One source of the acid drainage, the Dober mine, may be interconnected with the Hiawatha workings across the Iron River. Average 1975 water quality measurements as reported by the Western Upper Peninsula Planning and Development Region (1978) were: pH, 4.1; acidity, 2900 mg/hardness; specific conductance, 500 umhos/cm; iron, 1125 mg/l; manganese, 121 mg/l; and sulfate, 5130 mg/l. Acid waters from the Dober mine are ponded by the Stambough Sewage Treatment Plant. In May of 1975 the ponded water had a pH of 3.0 to 3.5 (WUPDR, 1978). Piles of pyrite-bearing black slate which were used to fill in the marshy area along the Iron River east of Caspian are a source of 10 percent of the acid drainage.

Subsidence in the area has been investigated by use of aerial photographs, mine maps, field investigations, and geophysical measurements. Conclusions related to these investigations (WUPDR, 1978) include:

- 1) More than 95% of visible subsidence affecting the surface in the Iron River District have occurred in sand and gravel above the bedrock;

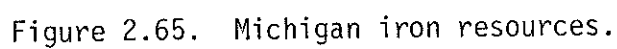
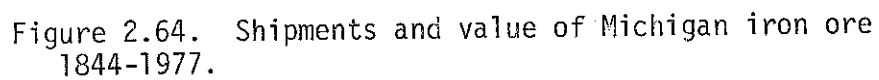


TABLE 2.4 - GENERAL STATISTICS COVERING PRODUCTION OF MICHIGAN IRON MINES FOR 1975, 1976,
AND 1977. (Adapted from R.C. Reed.)

<u>Range and Mine</u>	<u>Shipments in long tons</u>				
	Through 1974	1975	1976	1977	Total
<u>Marquette Range</u>					
Empire (OP)		4,493,969	5,000,040	3,958,622	
Mather (U)		154,404	131,514	71,866	
Pioneer Pellet Plant (processes Mather Ore)		1,268,746	1,324,868	751,663	
Republic-Humboldt (OP)		3,479,224	3,165,040	2,115,136	
Tilden (OP)		2,746,415	3,740,496	2,786,116	
Total	<u>427,133,498</u>	<u>12,142,758</u>	<u>13,361,958</u>	<u>9,683,403</u>	<u>462,371,617</u>
<u>Menominee Range</u>					
Groveland (OP)		1,993,283	2,020,643	2,117,066	
Sherwood (U)		242,186	305,309	215,239	
Total	<u>311,232,305</u>	<u>2,235,469</u>	<u>2,325,952</u>	<u>2,332,305</u>	<u>318,126,031</u>
<u>Gogebic Range</u>	<u>255,224,103</u>	<u>0</u>	<u>0</u>	<u>0</u>	<u>255,224,103</u>
State Totals	<u>993,639,906</u>	<u>14,378,227</u>	<u>15,687,910</u>	<u>12,015,708</u>	<u>1,035,721,751</u>

- 2) There is a close relationship between location voids and associated surface subsidence pits;
- 3) Subsidence has a greater occurrence over near surface stopes than over deep stopes; and
- 4) There are still areas of active subsidence.

In Gogebic County, ground water is recharging into the shafts of iron mines closed in 1967. Ground caving occurred in this area, in the 1930's, and in the Iron River-Crystal Falls area.

There are many abandoned iron mine shafts and pits in the southern part of Dickinson County. Sumps and pumps were maintained to remove excess water from many mine shafts and pits while the mines were in operation. When the mines were abandoned, water began to rise in the shafts and now is reported to pose problems for some areas:

"In the Hamilton Shaft of the Chapin Mine (2,300 foot-deep) the water has risen high enough to raise the water table and cause flooding of basements and storm drains in the northeast part of town. To eliminate this problem the city pumps over a million gallons a day from the shaft to its water plant during the summer; and two million gallons a day are pumped into Lake Antione in the winter. By following this procedure the water is maintained at a safe level and water drawn from Lake Antione into the city system is replaced.

In 1945 the mines at Norway were abandoned. Water began to rise in the shafts and flooding by ground water occurred in the low areas on the south-west side of the city. As much as two feet of water was reported in basements not equipped with sump pumps in December of 1949. The city, to relieve the flooding, installed a pump at 75 feet in the Aragon mine shaft. Present withdrawal is about 2,000 gpm. Pumping from the Aragon shaft has affected other shafts nearby to the east. The water from these shafts is extremely hard, but of fair quality. It is pumped into a small creek upstream from the city sewer outlet and dilutes the sewage in the stream" (Hendrickson and Doonan, 1966).

With respect to other environmental problems related to mining Hendrickson and Doonan note that:

- 1) Because the majority of mining activities occurred before State and Federal regulations came into effect, environmental concerns were not taken into consideration;
- 2) Poor record-keeping has left a void in location, production, and mine measurement information (depths--vertical and inclined, etc.);

- 3) Data and conclusions concerning environmental impacts of mining in the Upper and Lower Peninsula has just begun and, many years may elapse before all impacts are understood;
- 4) Tailings basins and ponds should be studied as a possible source of water contamination for Lake Milwaukee Sec. 8, 17, 20, 21, T 46N, R29W, and McKinnon Lake, Sec. 10, 15, T 47N, R 29W.

Silver

Silver-bearing veins of galena and metalliferous quartz have been reported in the Marquette, Gogebic and Iron River Districts of the Northern Peninsula, but the silver content is apparently too low for profitable mining (Lamey, 1935). In the Marquette District silver occurs in veins in Precambrian Huronian rocks and in the Gogebic District as "fissure seams" in brecciated quartzite layers. In these districts, the silver prospects are located in the same general localities as the gold-bearing veins. The Iron River silver district is shown in fig. 2.66 and 2.67.

Lamey noted that, "If the price of silver should become high enough, mining of some of the lead-silver veins might prove practicable."

Gold

Vein deposits of gold, by far the most important in Michigan, are concentrated in an area north of Ishpeming and Negaunee (Lamey, 1935). The first significant discovery of gold in Michigan occurred in 1880 northeast of the city of Ishpeming and led to development of the Ropes Mine (Allen, 1980). The gold occurs as native gold in a quartz vein in a Keewatin peridotite. By 1890 the Michigan mine located 2.5 miles west of the Ropes Mine was a significant producer from quartz veins in diorite. Approximately twenty other prospects were developed in this area. In 1890 gold was discovered in the Dead River area eight miles north of Ishpeming; this "find" was followed by a discovery by the Fire Centre Mining Company about 1892 in quartz veins in granite. The gross value of bullion from these mines is \$625,639.31 (table 2.5).

TABLE 2.5 - GROSS VALUE OF BULLION PRODUCED IN MICHIGAN'S MAJOR GOLD MINES (from Allen, 1980)

Ropes Gold & Silver Company	\$605,056.94
Michigan Gold Company	17,699.36
Fire Centre Gold Mining Company	2,063.00
Other Prospects	<u>820.00</u>
	\$625,639.31

Vein deposits have also been reported in the Marquette Range southwest of Palmer, the Gogebic Range near Lake Gogebic and southeast of Waverfield, and the Menominee Range south of Quinnesec. Since the closing of the Ropes Mine in 1897, there has been no gold produced in Michigan.

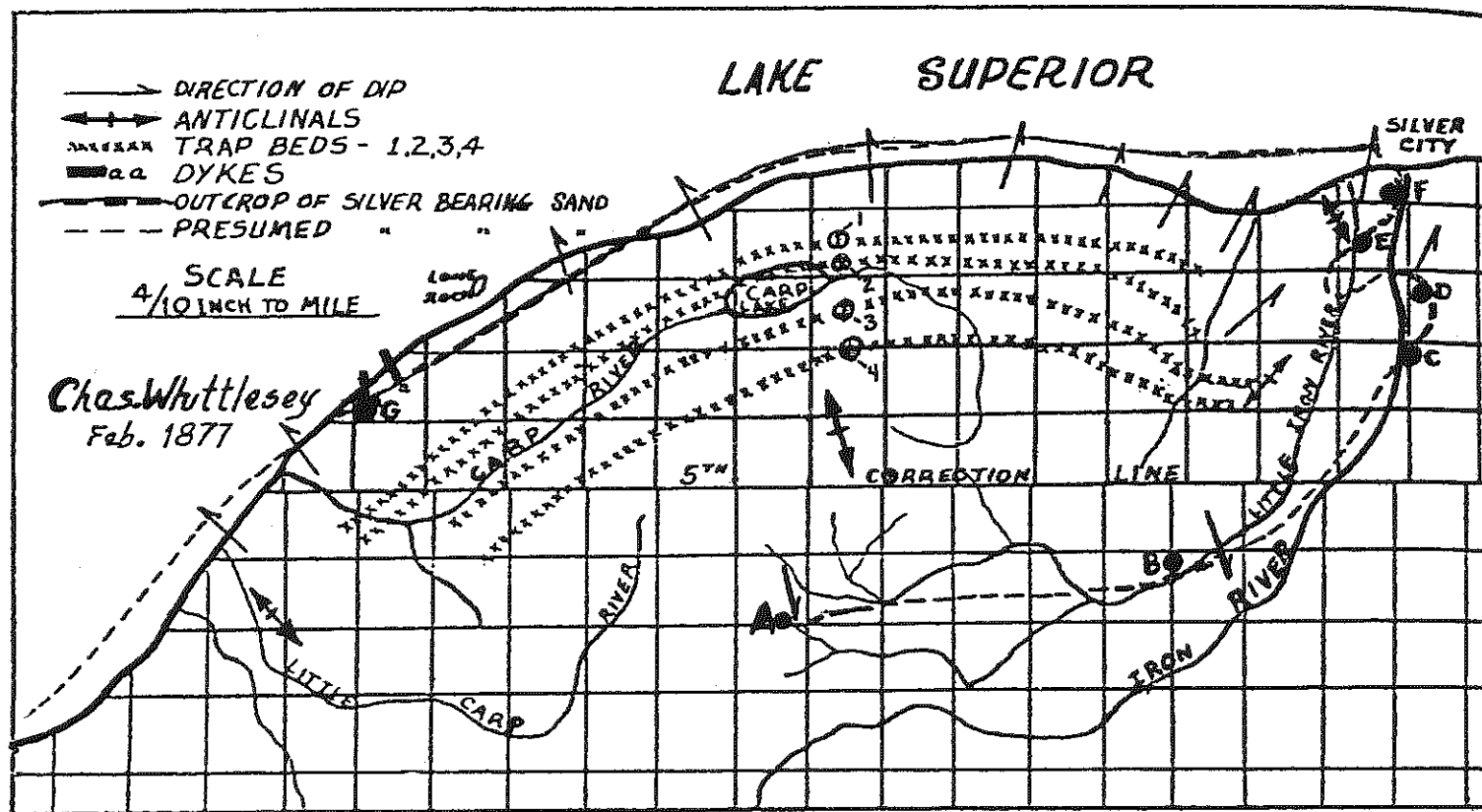


Figure 2.67. Outcrop of silver-bearing rocks in Carp River area.

Coal

Coal was first discovered in Jackson County, Michigan in 1835. From that time until 1950, 46,239,607 short tons have been produced from shaft mines located in the following counties: Bay, Calhoun, Eaton, Genesee, Huron, Ingham, Jackson, Midland, Saginaw, Shiawassee, and Tuscola (Cohee, et al., 1950). Production peaked in 1907 following the opening of underground mines in Saginaw and Bay Counties (fig. 2.68).

Michigan's coal basin, located in the central part of the Southern Peninsula covers 30,000 km² (fig. 2.69, pl. 17). Coal-bearing rocks occur as lenticular beds less than 1 meter thick in the Saginaw Formation of Lower Pennsylvanian age. The Saginaw Formation is 200-500 feet thick and includes gray-black shales, sandstones, shaly limestones, and coals. Most of the coal in this formation is of high volatile, bituminous rank and is beneath the water table.

Production of coal ended in 1950 due to competition from eastern fields even though substantial reserves remained (Stark and McDonald, 1980). Potentially recoverable reserves are estimated to be 115 million metric tons.

OIL AND GAS

Cambrian

No oil is presently produced from Cambrian rocks in Michigan. Cambrian oil is produced from the Cambrian Mt. Simon Sandstone in Ontario, Canada and from the Trempealeau (St. Lawrence) in Ohio. Recently, however, the Dart-PPG Edwards 7-36 well in Ruder Township of Missaukee County was drilled to a total depth of 10,810 feet. The well was completed in the top of the Prairie du Chien sandstone and tested 12.3 million cubic feet of gas (MM CF) per day and was rated at a calculated absolute open flow potential of 28 MM CF/day from 120 feet of pay (Oil and Gas News, April 10, 1981). The well has triggered a flurry of drilling and leasing in a 19-county area (fig. 2.70). The potential problems that waste injection may pose for future Cambrian oil and gas exploration in the Michigan Basin must be considered prior to installation of disposal wells in Cambrian Rocks.

Ordovician

According to the Michigan Geological Survey (1979) rocks of the Ordovician Trenton and Black River Groups have produced oil in the Michigan Basin since 1935 and gas since 1954 from 20 fields in 9 counties of south-central and southeast Michigan (fig. 2.71, pl. 31). Seven of the 20 fields have been abandoned. Through 1978, the Trenton-Black River produced 119,528,104 bbls of oil and 200,771,324 MCF of gas, 15.5% of Michigan's total oil production (769,045,772 bbls) and 14.6% of Michigan's total gas production (1,377,584,276 MCF). Peak oil production was reached in the

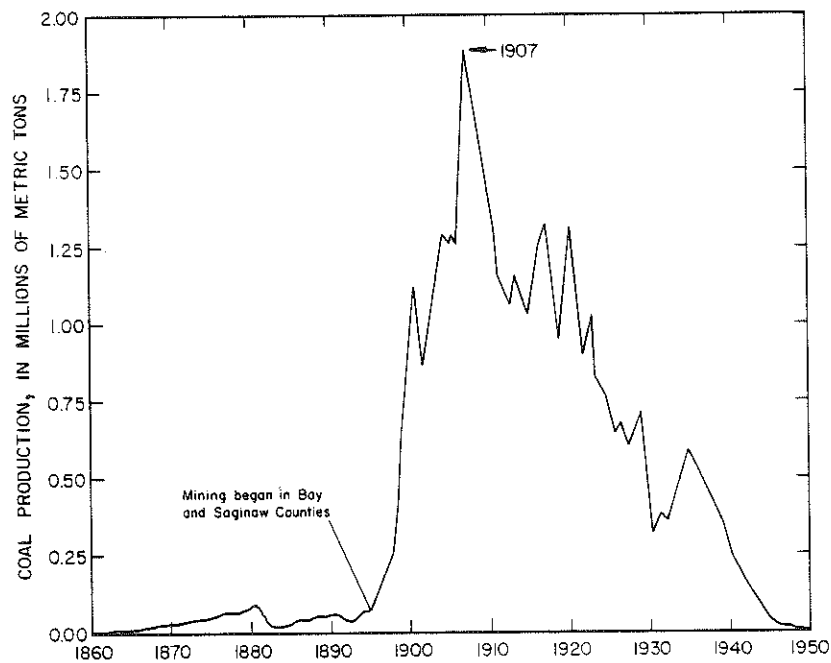


Figure 2.68. Coal production in Michigan 1860-1950.

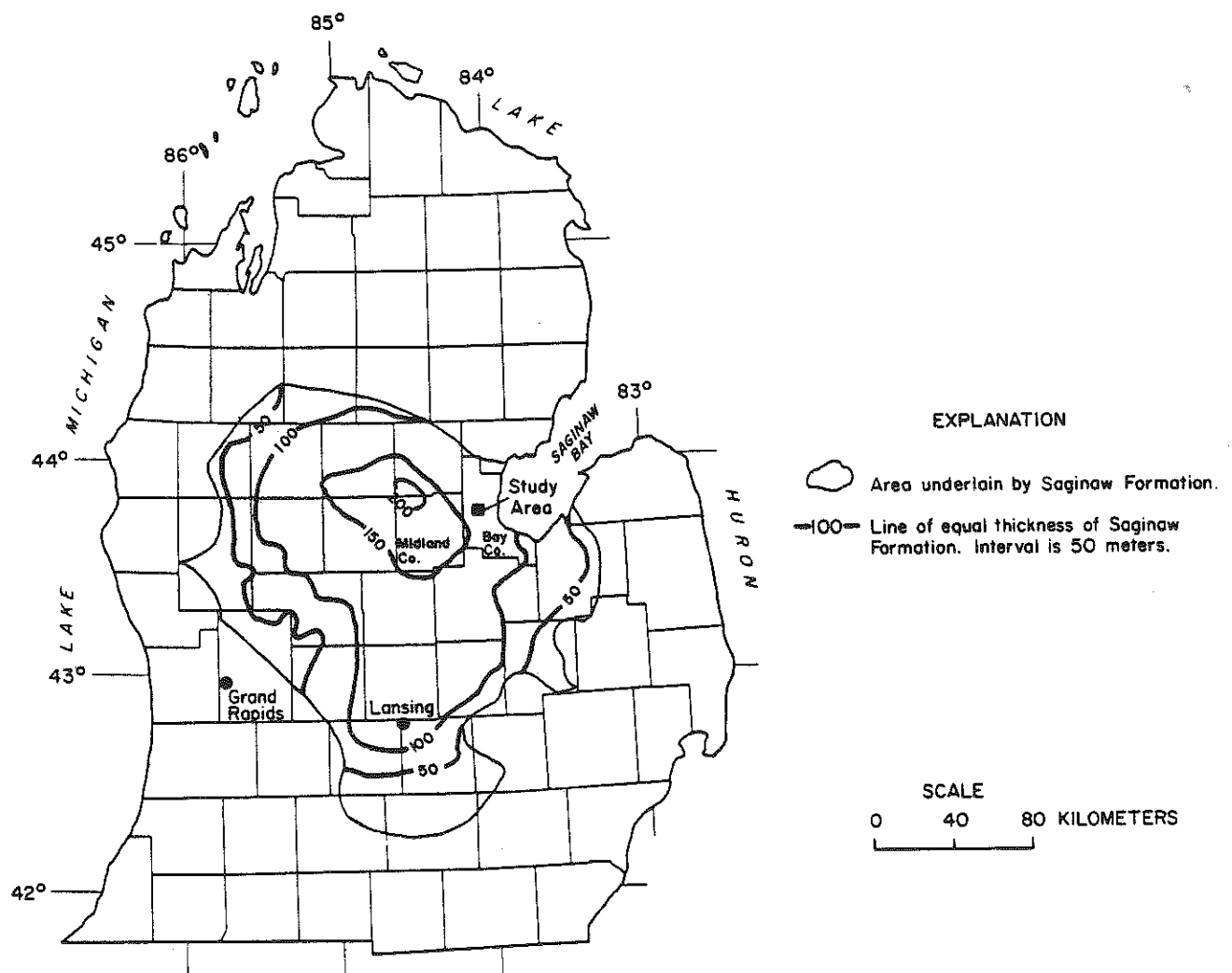


Figure 2.69. Thickness of the Saginaw Formation.

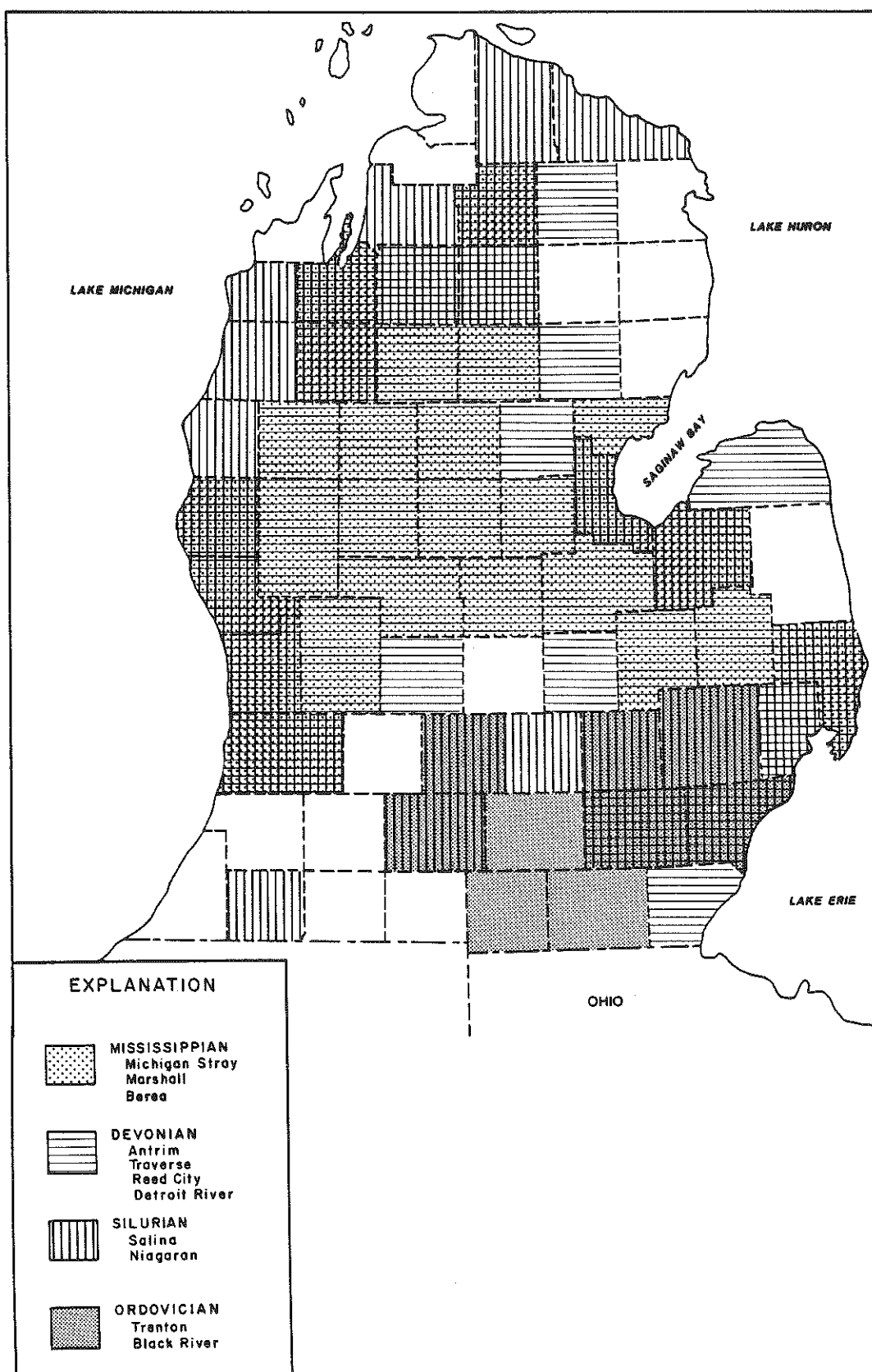


Figure 2.71. Oil and gas production in Michigan by county and geologic age. (From Michigan Geological Survey Oil and Gas, 1979.)

years 1960-1964, peak gas production from 1965-1969 (figs. 2.72 and 2.73). There have been no secondary recovery operations in the Ordovician, but the Trenton-Black River is used for gas storage in the Northville field, Wayne County (table 2.76).

Silurian

No oil or gas has been produced from the Lower Silurian (Cataract) Group. The Silurian Salina-Niagaran has produced oil in Michigan since 1952 and gas since 1929 from over 500 fields in 25 counties (fig. 2.71, pl. 31). Reefs have produced oil and gas in southeastern Michigan for many years with production peaking in the 1950's and early 1960's (Mesollela, 1974). Discoveries in the northern trend, with one exception, began in 1969 and currently include over 350 barrels of oil and 832,613,020 MCF gas, 17.3% of Michigan's total oil production and 59.8% of Michigan's total gas production. According to the Michigan Geological Survey (1980) peak production was reached in 1978 when 28,935,064 barrels of oil and 141,876,290 MCF gas were produced (figs. 2.72 and 2.73). This represented 83.5% of the oil and 94.3% of the gas produced in the state in 1978.

Of the 26 fields where pressure maintenance and secondary recovery operations has been used in Michigan since 1978 (table 2.7) 11 are in fields developed in Silurian Rocks. The fields are located in Calhoun, Ingham, Kalkaska, Manistee, Otsego, and St. Clair Counties. The Silurian is used for gas storage in 19 of the 36 gas storage fields in Michigan (table 2.6). Eighteen are in the Salina-Niagaran (5 in reefs) and one is in an A-2 solution cavern. All are located in six counties: Allegan, Barry, Calhoun, Livingston, Macomb, and St. Clair.

Devonian

The Devonian has produced oil in Michigan since 1927 and gas since 1929 from over 240 fields in 38 counties (fig. 2.71, pl. 31). No oil or gas has been produced from the Bois Blanc, Sylvania, Amherstburg, or Filer, but the Sylvania is an important brine producer. The Amherstburg is considered to have a very low hydrocarbon potential. The Filer Sandstone has not produced oil or gas, but is a source of brine in the Manistee area.

The Lucas Formation contains several oil and gas producing zones including the Richfield, "Sour Zones" and Reed City. Richfield permeabilities range from 4 to 6.5 millidarcies and the porosity ranges from 14 to 17 percent (Lilienthal, 1978). The Lucas Formation has also produced significant amounts of brine and salt from wells.

The Dundee-Rogers City zone has been the most prolific oil producer in Michigan (Lilienthal, 1978). Lost circulation and water zones may occur in lenticular zones in either limestone or dolomite. The Reed City, which occurs throughout the Basin, produces from vuggy and intercrystalline porosity in a dolomite beneath an anhydrite bed.

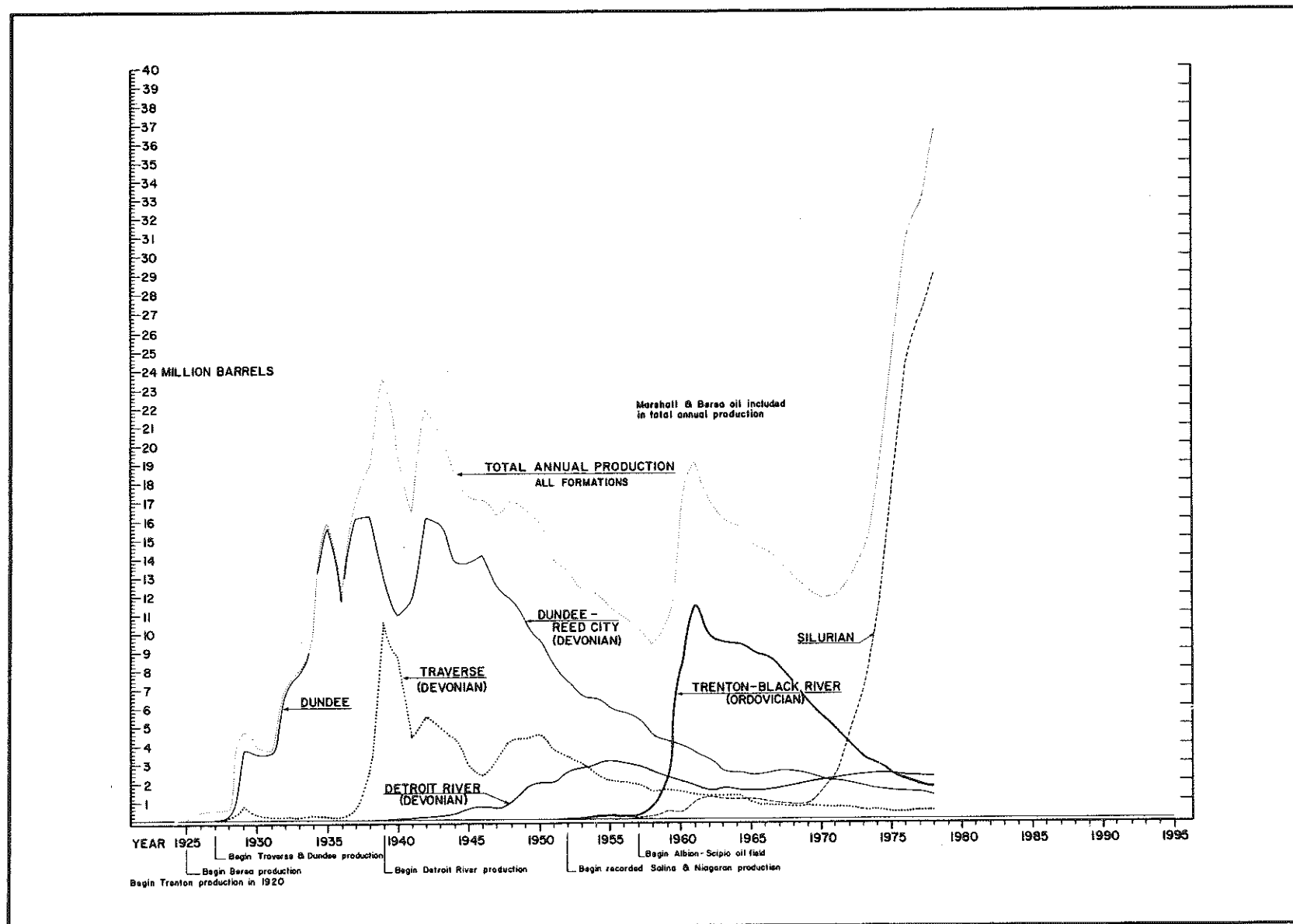


Figure 2.72. Trends in Michigan oil production by principal producing formations. (From Ellis et al., 1979.)

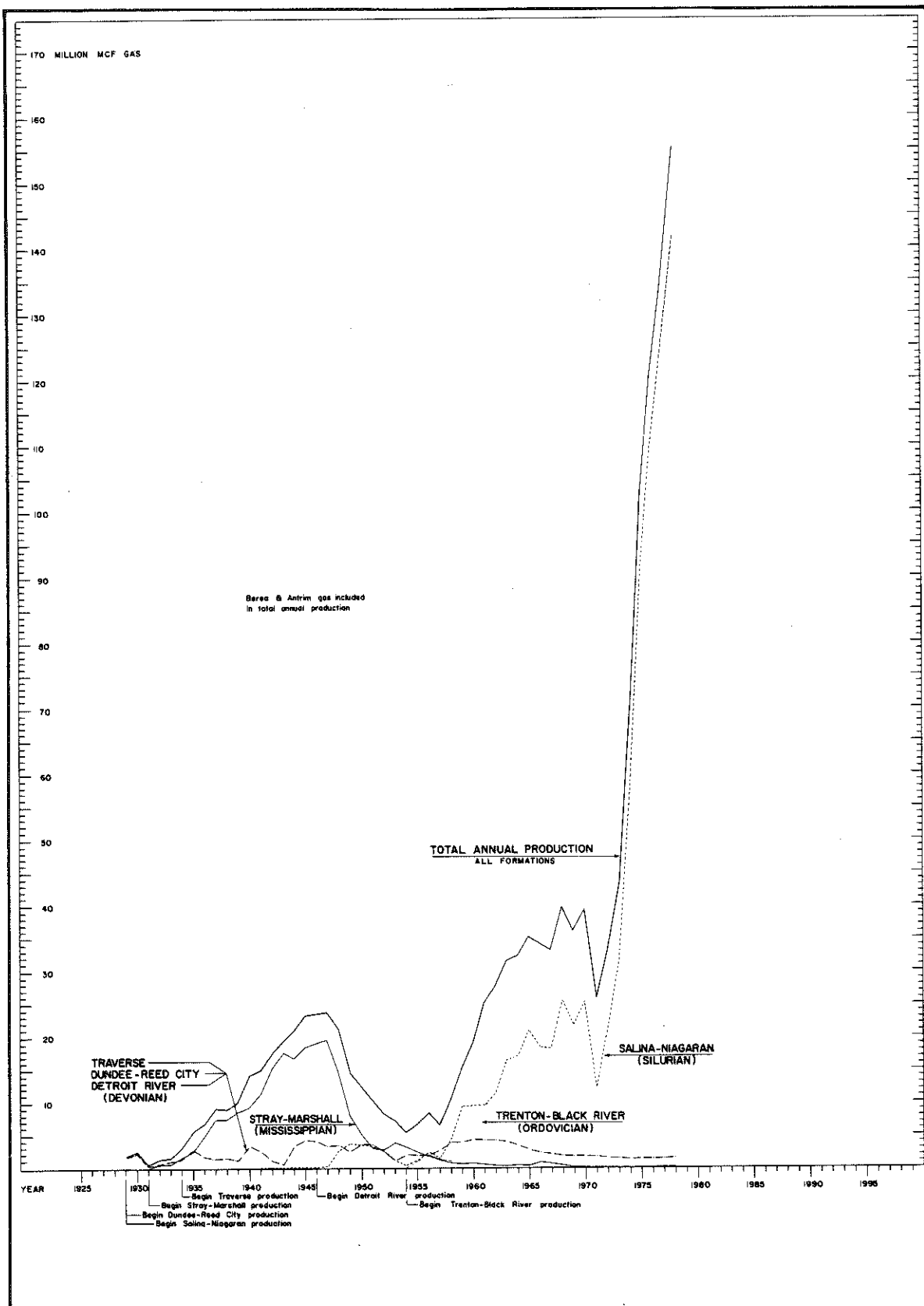


Figure 2.73. Trends in Michigan gas production by principal producing formations. (From Ells et al., 1979.)

TABLE 2.6 - GAS STORAGE FIELDS IN MICHIGAN.

POOL CLASSIFICATION										OF ACTIVE OIL FIELD OR POOL		GF ACTIVE GAS FIELD OR POOL		G-C ABANDONED GAS CONDENSATE FIELD OR POOL		GS GAS STORAGE RESERVOIR	
FIELD NAME		PRODUCING FORMATION	HEAD OF PRODUCING POOL	COUNTY	TOWNSHIP	DEPTH (IN FEET)	THICKNESS (IN FEET)	PAY ZONE	DEEPEST FORMATION (DEPTH OR POOL TESTED)	NUMBER OF WELLS TO COMPLETION	ABANDONED	OIL PRODUCTION - BBLs	GAS PRODUCTION - MCF	CUMULATIVE PRODUCTION 1978	RECOVERED OIL (BBLs)	TOTAL BAKERS PER DAY	
GS	AUSTIN	MICHIGAN STRAY	1933	PECOSTA	1,380	14	S		DETROIT RIVER	0	0	91	3,970		6,231,214		
GS	BELLE RIVER HILLS	SALINA-NIAGARAN	1961	ST. CLAIR	2,715	305	D	3, 4, 9, 10, 11, 12, 13, 14	COLEMAN TWP., 15N-5W, SECTIONS 27, 33	840	1,212		24,457,396				
GS	CLARENCE 19-15-5W	NIAGARAN REEF	1971	CALHOUN	3,156	24	D	NIAGARAN	3,240	1	0	1	160		1,057,656		
GS	COLONATER	MICHIGAN STRAY	1965	ISABELLA	1,590	10	S	ST. CLAIR	5,090	8	0	72	2,400		7,530,450		
GS	COLUMBUS	SALINA-NIAGARAN	1964	ST. CLAIR	2,738	190	D	CLINTON	3,232	0	0	20	320		13,588,373		
GS	COLUMBUS, WEST	SALINA-NIAGARAN REEF	1967	ST. CLAIR	3,183	14	D	CLINTON	3,447	29	0	0	25	520		16,613,514	
GS	CRANBERRY LAKE	MICHIGAN STRAY	1943	SUMMIT	1,321	10	S	CLINTON	5,201	0	0	171	7,000		7,600,200		
GS	CROTON	MARSHALL	1951	NEWAYGO	917	6	S	SALINA	3,993	0	0	60	860		1,347,252		
GS	FOUR CORNERS	SALINA-NIAGARAN	1966	ST. CLAIR	2,205	212	D	CLINTON	2,638	0	0	5	80		1,124,375		
GS	FREEMAN-LINCOLN	MICHIGAN STRAY	1938	CLARE	1,500	10	S	DETROIT RIVER	3,957	24	0	169	6,400		18,461,480		
GS	GOODWELL	MICHIGAN STRAY	1943	NEWAYGO	1,142	20	S	DETROIT RIVER	3,562	11	0	101	3,000		5,993,183		
GS	HAMILTON, NORTH	MICHIGAN STRAY	1952	CLARE	1,087	8	S	CLINTON	5,395	1	0	63	3,000		5,559,666		
GS	HESSEN	NIAGARAN REEF	1965	ST. CLAIR	2,499	261	D	NIAGARAN	2,887	3	0	21	640		11,747,204		
GS	HIDELL	SALINA-NIAGARAN	1935	LIVINGSTON	3,920	9	D	ST. PETER SS.	5,958	0	0	69	2,400		24,151,682		
GS	IRA	SALINA-NIAGARAN	1953	ST. CLAIR	2,276	33	D	CLINTON	2,632	0	0	15	600		3,588,639		
GS	LACEY STATION	4-2 SALT SOLUTION CAVERN	1971	BARRY				CAHRIAN		2	0	0	2				
GS	LEE 4-15-5W	SALINA-NIAGARAN REEF	1972	CALHOUN	3,162	46	D	NIAGARAN	3,415	2	0	2	320		716,595	1	
GS	LEE 16	SALINA-NIAGARAN		CALHOUN	3,200					1	0	0	1	300			
GS	LENDI	SALINA-NIAGARAN	1960	MACOMB	2,734	46	D	CLINTON	3,018	0	0	11	300		2,195,123		

63	MANITOW (WINFIELD)	MICHIGAN STRAY	1960	CLARE-OCEOLA	1,344	15	5		SYLVANIA	5,100	0	0	284	10,772		20,086,635				
WINFIELD TWP., 20N-6E, SECTION 17 THROUGH 21, 22 THROUGH 35, MEDINA TWP., 19N-04E, SECTIONS 1, 2, 3, 4, 6																				
65	MARTINVILLE	SALINA-MICHIGAN REEP	1966	MADISON	2,576	194	0		CLINTON	3,039	0	0	13	282		10,506,413				
SEE FOOTNOTE FOR GAS STORAGE FIELDS ON NEXT PAGE																				
65	NORTHVILLE	TRENTON- BLK. RIVER	1964	WAYNE-MASHSEWMA	3,395	70	0		CARLEBO- BROOKVIEW	5,050	0	0	69	3,834		16,301,766				
LENOX TWP., 4N-14E, SECTION 13																				
65	ORIENT	MICHIGAN STRAY	1945	OCEOLA-CLARE	1,508	11	5		SYLVANIA	5,307	1	0	76	2,600		5,457,873				
ORIENT TWP., 17N-7N, SECTIONS 2, 3, 10, 11, 12, 13, 16, GARFIELD TWP., 17N-6W, SECTIONS 18, 19																				
65	OVERSEL	SALINA	1936	ALLIANCE	2,650	12	0		TRENTON	4,060	0	0	106	6,666		14,937,949				
65	PARTELL	SALINA A-1	CARB	1959	OVERSEL TWP., 4N-14W, SECTIONS 4, 5, 8, 9, 10, 14, 15, 16, 21, 22, 23, 27, 28	5,192	30	0		TRENTON- BLK. RIVER	4,905	0	0	5	200		1,729,226			
65	PUTTIGR	SALINA-MICHIGAN	1960	LEE TWP., 15-SW, SECTIONS 12, 13	2,423	60	0		MICHIGAN	2,774	0	0	25	440		11,485,590				
CSTO TWP., 4N-15E, SECTIONS 11, 14, 15																				
65	RAY	SALINA-MICHIGAN	1961	MICHIGAN	2,945	101	0		MICHIGAN	3,223	0	0	47	660		35,907,293				
RAY TWP., 4N-13E, SECTIONS 1, 2, 11 ARNOLD TWP., 5N-13E, SECTION 36																				
65	REED CITY	MICHIGAN STRAY	1940	OSCEOLA-LAKE	1,217	12	5		ST. PETER SS.	8,960	0	0	105	4,080		7,795,091				
		REED CITY	1941		3,585	7	0			0	0	247				COMBINATION GAS STORAGE AND SECONDARY RECOVERY PROJECT - REFER TO TABLE 5 FOR ADDITIONAL DETAILS ON LIMITED OPERATION				
65	RIVERSIDE	MICHIGAN STRAY	1940	WISCONSIN	1,435	7	5		DUNDEE	3,953	0	0	99	3,660		5,292,251				
RIVERSIDE TWP., 21N-7W, SECTIONS 15, 16, 17, 19, 20, 21, 22, 23																				
65	SALCH	SALINA	1937	ALLIANCE	2,725	2	0		TRENTON	3,792	0	0	87	4,960		11,536,912				
SALCH TWP., 4N-13W, SECTIONS 2, 3, 9, 10, 11, 12, 14, 15, 16, 17, 21, 22, 23, JAMESSTOWN TWP., 5N-13W, SECTIONS 34, 35																				
65	SCOTCH (SCOTCH, NEW HAVEN)	MICHIGAN STRAY	1935	GALETON-MONTICM	.020	11	5		DUNDEE	3,536	3	3	56	3,910		11,337,206				
NEW HAVEN TWP., 10N-4W, SECTIONS 2, 3, 4, 5, 8, 9, 10, 11 SUMNER TWP., 11N-4W, SECTIONS 31, 32, 33, 34																				
65	SIX LAKES	MICHIGAN STRAY	1934	CENTRAL TWP., 10N-5W, SECTIONS 1, 2, 3, 5, 6, FERRIS TWP., 11N-5W, SECTIONS 22, 26	1,210	25	5		DETROIT RIVER	3,730	19	61	256	11,486		52,636,813				
NORFOLK TWP., 13N-6W, SECTIONS 23, 25, 26 THROUGH TWP., 13N-6W, SECTIONS 23, 24, 25 HILLMAN TWP., 13N-7W, SECTIONS 27 THROUGH 36																				
REVEREND TWP., 12N-7W, SECTIONS 1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 14, 15, 16, 17, 18, 20, 21																				
65	SHAW CREEK	SALINA-MICHIGAN	1967	ST. CLAIR	2,256	245	0		CLINTON	2,638	0	0	1	40		447,539				
CASCO TWP., 4N-15E, SECTION 36																				
65	WINEFIELD	MICHIGAN STRAY	1935	MONTICM	1,123	8	5		DETROIT RIVER	3,405	2	0	127	3,240		4,932,895				
65	WINDVILLE (NORWICH)	MICHIGAN STRAY	1943	WINEFIELD TWP., 13N-9W, SECTIONS 6, 7, 8, 16, 17, 18 REYNOLDS TWP., 12N-10W, SECTIONS 1, 12	1,185	13	5		DETROIT RIVER	3,405	0	0	46	2,240		2,736,924				
NORWICH TWP., 15N-11W, SECTIONS 16, 17, 20, 21, 28, 29																				
															TOTALS:	99,235	0	125,931	215	366,774,851

BATTLE CREEK GAS COMPANY
LACEY STATION
CONSUMERS POWER COMPANY
FOUR CORNERS
MESSEAN
INA
LEMON
MONTVILLE
OVERSEL
PUTTIGOUT
RAY
SALEM
SPAN CREEK

MSU DEVELOPMENT COMPANY
CLARENCE 19-15-4M
MICHIGAN CONSOLIDATED GAS COMPANY
AUSTIN
BELLE RIVER MILLS
COLUMBUS
COLUMBUS, WEST
FREEMAN-LINCOLN
GOODWELL
HAMILTON, NORTH
ORIENT

REED CITY
519 LAKES
SHAWVER (SUNNER-NEW HAVEN)
MOODYVILLE
MICHIGAN GAS STORAGE COMPANY
MARION
CRANBERRY LAKE
RIVERSIDE
MICHIGAN GAS UTILITIES COMPANY
LEE 4-415-W
LEE 16

MICHIGAN-MISCOMIN PIPELINE COMPANY
CAPAC (BEING DEVELOPED)
CROTON
COLUMBIANA
MORTONVILLE
WINTFIELD
PARMALEND EASTERN PIPELINE
HONOLULU
SOUTHEASTERN MICHIGAN GAS COMPANY
MARTINSVILLE-MORTON

FIELD AND COUNTY	OPERATOR TYPE OF PROJECT	DISC. YEAR PROJECT BEGAN	PAY ZONE			TOTAL UNIT ACRES	INJECTION FLUIDS	VOLUME OF INJECTED FLUID 1978			CUMULATIVE VOLUME OF INJECTED FLUID		UNIT PRODUCTION IN 1978					UNIT CUMULATIVE 1-1-79		
			FORM.	THICK	DEPTH			PRESSURE PSIG	MCF GAS	BARRELS WATER	INJ. WELLS	MCF GAS	BARRELS WATER	BARRELS OIL	SALES MCF GAS	WATER PRODUCED	NO. WELLS	BARRELS OIL	SALES MCF GAS	BARRELS WATER
AURELIUS 35 UNIT INGHAM CO.	(1)UWF	1971 1974	NIAG.	110	4075	400	BRINE 1024		NONE	831,556	2	NONE	3,165,856	(P) NONE (S) 186,617	98,510	520,000	5	(P) 805,000 (S) 789,986	847,168	1,025,790
BEAVER CREEK CRAWFORD-KALKASKA CO.	(2)UWF	1947 1963	RICH.	17	4400	4640	FRESH WATER 2229		NONE	5,353,174	60	NONE	74,830,056	(P) NONE (S) 516,222	194,100	524,892	55	(P) 7,750,000 (S) 4,689,588	19,535,535	4,934,578
BEAVERTON, WEST GLADWIN CO.	(3)UWF	1943 1966	DD.	2	3876	480	FRESH WATER & BRINE, 2100		NONE	130,737	2	NONE	840,499	(P) NONE (S) 4,656	NONE	10,950	4	(P) 180,000 (S) 44,198	NONE	87,420
BENTLEY DUNDEE GLADWIN CO.	(4)UWF	1937 1964	DD.	13	3510	440	FRESH WATER & BRINE, 2232		NONE	148,430	4	NONE	1,476,161	(P) NONE (S) 12,554	NONE	21,900	7	(P) 382,000 (S) 111,328	NONE	488,590
BERLIN ST. CLAIR CO.	(12)UWF	1960 1970	NIAG.	30	3800	200	BRINE VACUUM		NONE	11,700	1	NONE	1,670,499	(P) 648 (S) NONE	NONE	12,775	2	(P) 348,308 (S) 27,536	NONE	85,411
CHESTER 18 OTSEGO CO.	(11)UWF	1971 1978	NIAG.	20	6330	1280	FRESH WATER VACUUM		NONE	200,000	7	NONE	200,000	(P) 780,877 (S) NONE	1,004,405	86,870	11	(P) 5,662,854 (S) NONE	4,067,054	181,377
COLUMBUS 3 UNIT ST. CLAIR CO.	(5)UWF&WF	1968 1974	NIAG.	49	3105	860	RECYCLE GAS & BRINE, 2232		579,094	28,011	2 GAS 1 WTR	1,865,996	91,535	(P) NONE (S) 390,308	NONE	28,000	19	(P) 3,275,000 (S) 1,246,317	NONE	308,870
CRANBERRY LAKE CLARE CO.	(4)UWF	1951 1969	RICH.	15	5048	680	FRESH WATER 2700		NONE	400,753	8	NONE	3,484,170	(P) 11,344 (S) 64,663	NONE	100,375	7	(P) 1,128,737 (S) 236,341	NONE	653,715
EAST HORNWICH HISSAUKEE CO.	(5)URG&WF	1942 1947	RICH.	14	4880	4880	FRESH WATER 2450	DISCONT. 1962		1,332,048	56	11,699,478	21,400,311	(P) NONE (S) 359,857	294,715	286,890	69	(P) 5,800,000 (S) 5,409,053	10,423,560	2,637,049
ENTERPRISE HISSAUKEE CO.	(5)URG&WF	1943 1953	RICH.	16	4405	1320	FRESH WATER 2500	DISCONT. 1961		883,945	16	1,419,641	8,547,983	(P) NONE (S) 111,499	88,064	64,240	17	(P) 1,925,000 (S) 1,408,282	1,556,829	968,031
GROUT GLADWIN CO.	(5)UWF	1956 1960	RICH.	10	5039	480	FRESH WATER 2250		NONE	266,734	5	NONE	3,653,179	(P) NONE (S) 28,701	NONE	132,860	7	(P) 900,000 (S) 886,030	NONE	1,204,197
HAMILTON CLARE CO.	(5)UWF	1952 1958	RICH.	12	5145	1800	FRESH WATER 2225		NONE	954,813	17	NONE	18,829,872	(P) NONE (S) 121,904	46,172	582,540	26	(P) 2,800,000 (S) 3,651,854	4,159,792	5,683,641
HEADQUARTERS ROSCOMMON CO.	(7)UWF	1952 1969	RICH.	13	4946	720	FRESH WATER 2444		NONE	157,297	8	NONE	3,328,950	(P) NONE (S) 38,119	NONE	44,238	10	(P) 722,000 (S) 451,042	NONE	424,805
KALKASKA 21 POOL C KALKASKA CO.	(10)URG	1972 1977	NIAG.	130	6600	1040	RECYCLE GAS 1850		301,004	NONE	1	306,177 ^A	NONE	(P) 68,769 (S) 3,619	11,922	NONE	1	(P) 760,091 (S) 3,619	1,257,871	NONE
KALKASKA 21 POOL D KALKASKA CO.	(10)URG	1971 1976	NIAG.	170	6590	1040	RECYCLE GAS 1700		329,005	NONE	1	721,658 ^B	NONE	(P) 91,828 (S) 30,610	6,237	NONE	1	(P) 1,264,777 (S) 40,610	1,810,250	NONE
MANISTEE 1 UNIT MANISTEE CO.	(11)URG	1973 1976	NIAG.	158	4440	320	RECYCLE GAS 1700		474,217	NONE	1	1,190,115 ^C	NONE	(P) 100,115 (S) 5,269	83,788	NONE	1	(P) 390,699 (S) 5,269	115,071	NONE
ONONDAGA 10 UNIT INGHAM CO.	(1)UWF	1971 1973	NIAG.	75	3784	1760	BRINE 633		NONE	5,034,075	7	NONE	14,975,046	(P) NONE (S) 876,235	1,388,429	1,708,200	15	(P) 2,703,000 (S) 3,240,150	6,143,161	2,888,552
ONONDAGA 21A UNIT INGHAM CO.	(1)UWF	1971 1978	NIAG.	65	3629	1120	BRINE 545		NONE	501,573	3	NONE	501,573	(P) 97,860 (S) NONE	588,705	43,070	12	(P) 1,513,018 (S) NONE	4,185,585	43,070
ONONDAGA 21B UNIT INGHAM CO.	(1)UWF	1971 1978	NIAG.	59	3688	480	BRINE 372		NONE	1,224,578	3	NONE	1,224,578	(P) 109,342 (S) NONE	164,315	84,680	4	(P) 1,541,293 (S) NONE	1,462,361	84,680
PENNFIELD 35 UNIT CALHOUN CO.	(1)UWF	1974 1976	NIAG.	4	2820	1360	BRINE 744		NONE	1,052,088	5	NONE	1,790,941	(P) 284,416 (S) 115,000	150,836	699,340	11	(P) 1,289,669 (S) 215,000	314,162	793,328
REED CITY** LAKE-OSCEOLA CO.	(8)GSOR	1940 1963	DD. R.C.	21	3585	5000	PRODUCED BRINE EXTRANEUS GAS		-3,570,000	942,065	174 GAS 10 WTR	39,719,534	154,587,861	(P) NONE (S) 145,040	NONE	942,065	171	(P) 39,293,000 (S) 3,086,163	16,257,876	174,622,889
ROSE CITY OGEMAW CO.	(9)UWF	1945 1964	RICH.	9	4125	4600	FRESH WATER 2489		NONE	563,636	38	NONE	6,566,172	(P) NONE (S) 208,020	126,140	25,368	46	(P) 3,558,000 (S) 1,549,891	6,545,111	408,253
ROSE CITY, CENTRAL OGEMAW CO.	(9)UWF	1951 1971	RICH.	8	4125	1560	FRESH WATER 2209		NONE	328,498	9	NONE	2,510,197	(P) NONE (S) 17,708	4,067	1,643	10	(P) 1,000,000 (S) 139,013	993,602	84,390
ROSE CITY, WEST OGEMAW CO.	(5)UWF	1952 1968	RICH.	10	4150	320	FRESH WATER & BRINE, VACUUM		NONE	146,625	5	NONE	2,283,330	(P) NONE (S) 22,263	4,516	16,060	4	(P) 570,000 (S) 231,411	847,639	116,525
ST. HELEN ROSCOMMON CO.	(5)URG&WF	1941 1958	RICH.	9	4480	4480	FRESH WATER VACUUM	DISCONT. 1959		811,330	41	3,151,610	12,800,040	(P) 222 (S) 271,516	225,979	81,030	48	(P) 3,760,000 (S) 2,361,389	11,397,216	1,018,926
WEST BRANCH OGEMAW CO.	(6)UWF	1933 1966	DD.	28	2650	2730	FRESH WATER & BRINE, 1500		NONE	1,151,894	54	NONE	7,242,556	(P) 36,176 (S) 205,100	NONE	789,395	65	(P) 3,479,352 (S) 941,565	NONE	3,703,824

TABLE 2.7 - PRESSURE MAINTENANCE AND SECONDARY RECOVERY OPERATIONS. (From Ellis et al., 1979.)

NUMBER OF ACTIVE PROJECTS 26
 AMOUNT OF GAS INJECTED IN 1978 1,683,320 MCF
 AMOUNT OF WATER INJECTED IN 1978 22,613,373 BBL
 NUMBER OF GAS INJECTION WELLS 179
 NUMBER OF WATER INJECTION WELLS 362
 TOTAL PRIMARY OIL PRODUCTION IN 1978 . . . 1,582,375 BBL
 TOTAL SECONDARY OIL PRODUCTION IN 1978 . . 3,735,480 BBL

OIL PRODUCTION IN EXCESS OF THAT EXPECTED THROUGH PRIMARY DEPLETION IN THE PRESSURE MAINTENANCE AND SECONDARY RECOVERY PROJECTS IS APPROXIMATELY 11% OF THE TOTAL MICHIGAN PRODUCTION FOR 1978.

TOTAL UNIT ACRES AND OTHER DATA DOES NOT NECESSARILY CORRESPOND WITH DRILLED ACRES AS NOTED ON TABLES 2 AND 3.

- A. INCLUDES 86,917 MCF PURCHASED FROM OUTSIDE KALKASKA 21 POOL C.
 B. INCLUDES 110,717 MCF PURCHASED FROM OUTSIDE KALKASKA 21 POOL D.
 C. INCLUDES 161,584 MCF PURCHASED FROM OUTSIDE MANISTEE 1 UNIT.

(S)*36,456 BBL. OF SECONDARY OIL CREDITED TO WEST BRANCH PROJECT ARE FROM TWO TRAVERSE FORMATION WATER SOURCE WELLS.

FIGURES DEFINED AS (P) AND (S) RESPECTIVELY REPRESENT OIL PRODUCED AS A RESULT OF PRIMARY AND SECONDARY TECHNIQUES.

COMPILATIONS ON PRESSURE MAINTENANCE AND SECONDARY RECOVERY OPERATIONS PROVIDED BY STAFF MEMBERS OF THE PRODUCTION AND PRORATION UNIT.

THERE ARE THREE SEPARATE PRESSURE MAINTENANCE AND SECONDARY RECOVERY OPERATION UNITS IN THE ROSE CITY FIELD, OCEANAW COUNTY. THEY ARE CALLED ROSE CITY, ROSE CITY, CENTRAL AND ROSE CITY, WEST. NOT ALL PRODUCING WELLS IN THE FIELD ARE INCLUDED IN THE UNITS.

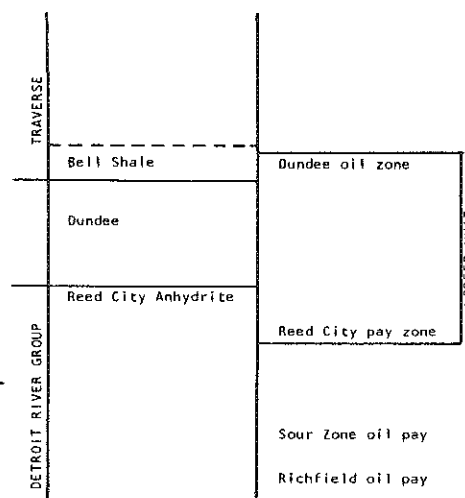
OPERATOR

- (1) MOBIL OIL CORPORATION
- (2) UNION OIL CORPORATION
- (3) H. E. TOPE, INC.
- (4) LEASE MANAGEMENT, INC.
- (5) SUN OIL COMPANY
- (6) MARATHON OIL COMPANY
- (7) FARMERS PETROLEUM COOPERATIVE, INC.
- (8) MICHIGAN CONSOLIDATED GAS COMPANY
- (9) MUSKEGON DEVELOPMENT COMPANY
- (10) NORTHERN MICHIGAN EXPLORATION COMPANY
- (11) SHELL OIL COMPANY
- (12) LOEB OIL COMPANY

PROJECT TYPE

- UWF UNIT WATER FLOOD
 URGWF UNIT RECYCLED GAS & WATER FLOOD
 GSOR UNIT GAS STORAGE IN OIL RESERVOIR

**LOREED UNIT IN REED CITY FIELD



NOTE: THE LOREED UNIT IN THE REED CITY FIELD, A MULTI-POOL FIELD, IS A GAS STORAGE-SECONDARY OIL RECOVERY OPERATION ENCOMPASSING SEVERAL RESERVOIRS. THE RESERVOIR FORMATIONS INCLUDED IN THE LOREED UNIT ARE SHOWN IN THE STRATIGRAPHIC SECTION.

THE RICHMOND UNIT, LISTED IN THIS TABLE IN 1975 AND IN PREVIOUS ISSUES HAS BEEN DELETED FROM THE TABLE. THE RICHMOND UNIT PRODUCES FROM THE DETROIT RIVER SOUR ZONE. IT SHOULD NOT BE CONSIDERED AS A FIELD. IT IS THE NAME APPLIED TO THE DETROIT RIVER SOUR ZONE POOL RESERVOIR IN THE REED CITY FIELD. THE FORMER RICHMOND PROJECT IS NOT RELATED TO THE LOREED OPERATION.

The Traverse Limestone has produced oil and gas since the late 1920's, mostly in southwest Michigan from structures, porosity pinchouts and small bioherms where it is predominantly carbonate. It contains a series of porosity zones, many of which can be traced over large areas and may cause lost circulation or produce hydrocarbons. Permeabilities up to 100 millidarcies have been reported (Lilienthal, 1974).

Some wells in Otsego County have produced gas from the Antrim Shale, but shows of oil have rarely been recorded. Oil and gas has been produced from the Ellsworth carbonates and the Berea Sandstone has produced oil and gas in eastern Michigan since 1925. Perhaps the greatest hydrocarbon potential from the Antrim and Ellsworth is from in situ burning. A pilot program has been underway in Michigan to evaluate the feasibility of this method (see Section 4). The Sunbury has not produced oil or gas.

Peak production from the Dundee-Traverse was reached in the 1940's when over 175,147,000 bbls oil and over 28,847,000 MCF gas were produced (figs. 2.72 and 2.73). Peak production from the Detroit River was reached in the late 1950's (1955-1959), when 13,716,790 bbls oil were produced. Gas production from the Detroit River peaked in 1960-1964 when 19,252,334 MCF gas were produced. In 1978, 4,010,272 bbls oil and 1,185,502 MCF gas were produced from the Detroit River representing 12 percent and 8 percent respectively of Michigan production as compared with 99 percent of the oil production from 1955 to 1959 and 31 percent of the gas production from 1955 to 1959.

Pressure maintenance and secondary recovery operations have injected fresh water, brine and extraneous gas since 1933 into the Richfield and Dundee Formations at 15 of the 26 fields where these methods have been employed (table 2.8). The fields are located in Clare, Crawford, Kalkaska, Gladwin, Missaukee, Ogemaw, and Roscommon Counties (pl. 31). The Devonian is used for gas storage in only one field in Michigan in Osceola and Lake Counties (table 2.7).

Mississippian

The Mississippian has produced oil in Michigan since 1925 and gas since 1931 from more than 95 fields in 27 counties (fig. 2.71, pl. 31). Shows of oil have been reported in the Coldwater sandstones from eastern Michigan and in the limestones from western Michigan. Also, a few gas wells have been completed in the Coldwater "Weir sand" (Lilienthal, 1978). The Berea Sandstone and the Marshall Sandstone have produced some oil and gas, and brine is produced from the Marshall in Gratiot County. The overlying Michigan "Stray Sandstone" has produced large quantities of gas since 1929 and is used as a gas storage reservoir. Possibilities for oil and gas production from the Upper Mississippian Bayport Limestone appear slight.

Peak oil production from the Berea was reached in the period 1925-29 (fig. 2.72) and gas in the period 1940-44 (fig. 2.73). Peak oil production in the Marshall was reached during the period 1940-44 and gas during the period 1945-49. In 1978, the Mississippian produced only 20,629 bbls oil and 71,260 MCF gas, 0.001 percent of Michigan's total oil production and 0.01 percent of Michigan's total gas production.

There are no pressure maintenance or secondary recovery operations in the Mississippian. The Mississippian is used for gas storage in 13 of the 36 storage fields in Michigan in Clare, Gratiot, Lake, Mecosta, Missaukee, Montcalm, Newaygo, Osceola, and St. Clair Counties.

Pennsylvanian

Of Pennsylvanian rocks in Michigan, only the Saginaw Formation has produced hydrocarbons. Gas has been produced from a single field developed in this unit.

SEISMICITY

Michigan lies within the area known as Zone 1 on the U.S. Coast and Geodetic Survey Seismic Risk Map. In this zone only minor damage should be expected corresponding to maximum Modified Mercalli Intensities of V and VI. Historical records include accounts of earthquakes felt in Michigan as early as 1638. The greatest earthquake known to have occurred in the Midwest was the New Madrid earthquake, one of a series of earthquakes that occurred between 1811 and 1813 centered in the tri-state area of Illinois, Missouri, and Kentucky. According to von Hake, as many as nine tremors from these earthquakes were felt in the Detroit region (Bricker, 1977). Other earthquakes with epicenters located in states throughout the Midwest have produced intensities of up to VII in Michigan. One of the most recent occurred in north-central Kentucky in 1980. A principal source of earthquakes felt in Michigan is the Lima, Ohio areas (fig. 2.74).

Thirty-four earthquake epicenters were located within the state of Michigan between 1872 and 1967, 30 due to activity along faults and 4 associated with mining operations (table 2.8, pl. 19). Seismic events related to faults are thought to have originated at depths of 12 to 70 miles in the lower crust and upper mantle. They apparently have not involved the overlying Paleozoic section. Two earthquakes with intensities of VIII have been ascribed to mining operations or fault movements in the Keweenaw Peninsula between 1905 and 1906 resulting in deformation of railroad tracks and ground subsidence (Bricker, 1977). Ground subsidence capable of producing felt earthquakes in Michigan has also occurred over abandoned coal mine shafts in the Saginaw-Bay City area, gypsum mines near Grand Rapids, and salt caverns in the Detroit area.

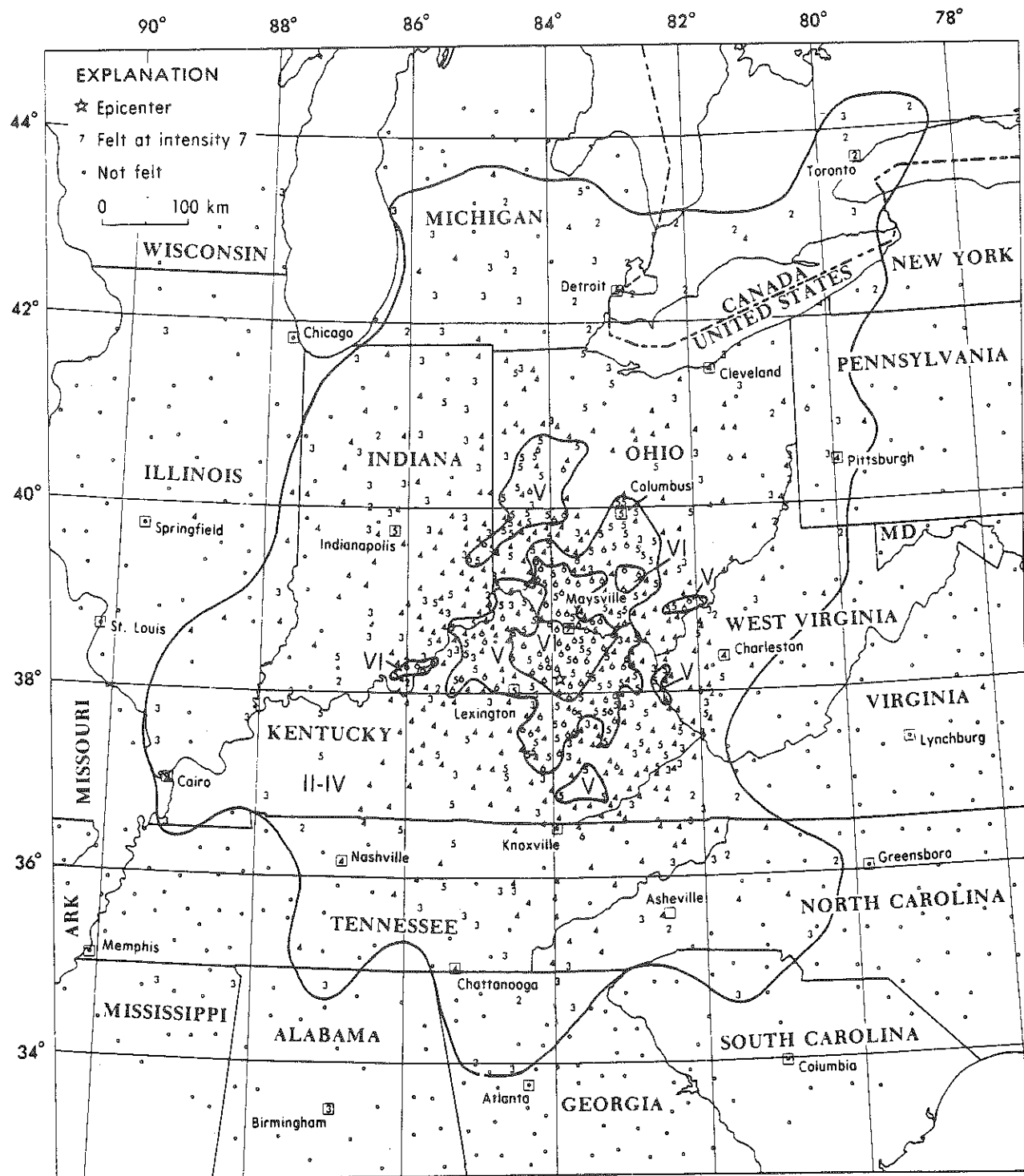


Figure 2.74. Isoseismal map for the Kentucky earthquake of 27 July 1980, UTC by C.W. Stover.

TABLE 2.8 - RECORDED SEISMIC DISTURBANCES.

LOCALITY	NORTH LAT.	WEST LONG.	YEAR	DATE	INTENSITY MOD. MERCALLI SCALE
Adrian	41.53	84.03	1876	Jan. 27	III*
Alamo	42.30	85.60	1883	Feb. 4	VI
Burlington	42.00	85.00	1947	Aug. 9	VI
Calumet	47.16	88.25	1905	July 26	VII-VII
	47.16	88.25	1915	Mar. 3	IV-V
	47.16	88.25	1918	Oct. 1	III
	47.16	88.25	1955	Jan. 5	IV
Capac	43.0	83.0	1968	Oct. 31	III*
Detroit	42.22	83.10	1876	Feb. 27	--
	42.22	83.10	1877	Aug. 17	IV
	42.22	83.10	1939	Mar. 13	IV
Escanaba	45.44	87.05	1939	July 18	II-III
	45.44	87.05	1939	Aug. 1	II-III
	45.44	87.05	1939	Nov. 7	III*
	45.44	87.05	1943	Feb. 15	--
	45.44	87.05	1944	Nov. 16	II-IV
	45.44	87.05	1944	Dec. 10	II-IV
	45.44	87.05	1945	May 18	II
Grand Rapids	42.57	85.41	1906	May 19	III*
Hancock	47.08	88.37	1906	Apr. 20	--
	47.08	88.37	1955	Jan. 6	V
Houghton	47.07	88.33	1906	Feb. 9	--
	47.07	88.33	1906	Nov. 9	--*
	47.07	88.33	1909	Jan. 22-23	V
Lansing	42.45	84.35	1967	Feb. 2	IV
Menominee	45.05	87.40	1905	Mar. 13	V
	45.08	87.40	1907	Jan. 10	--
Morrice	42.51	84.11	1918	Feb. 22	IV
Negaunee	46.40	87.6	1934	May 7	--*
	46.30	87.37	1935	October	II-III
Newberry	46.22	85.31	1933	Jan. 29	II
Niles	41.50	86.16	1897	Oct. 31	--
Oskar	47.30	88.40	1906	May 26	VIII
	47.30	88.40	1906	Aug. 8	IV*
	47.30	88.40	1915	Oct. 4	V*
Pontiac	42.60	83.40	1930	Nov. 20	III*
Port Huron	42.58	82.28	1922	Mar. 16	III
St. Joseph	42.05	86.31	1899	Oct. 10	IV
Sault Ste. Marie	46.19	84.22	1905	Apr. 14	--
	46.29	84.24	1930	Jan. 23	III
Wenona	43.40	83.54	1872	Feb. 6	IV
Winona	46.90	88.90	1872	Feb. 6	IV*

* Stover, 1980

BOTTOM HOLE PRESSURE DATA

The data on bottom hole pressures for oil and gas wells in Michigan are on file in the Oil and Gas Section in the Michigan DNR office in Lansing. Data for the northern reef and Albion-Scipio trends (Ingham, Calhoun, Eaton, Livingston, and St. Clair Counties), are contained in three standing files; data for the remainder of the state are scattered throughout other files, e.g. historical. There is no standardized data sheet other than that used by a few oil companies. Data is on several typed or BHP test sheets submitted by different oil companies, on DNR forms, or hand-written on sheets of loose leaf paper. Where multiple BHP surveys may have been conducted on individual wells, several sheets are present. Table 2.9 illustrates the available data. Permit numbers are not always listed on the forms. Overall, the data would be difficult to retrieve owing to the volume, and general lack of organization.

TABLE 2.9 - BOTTOM HOLE PRESSURE DATA (from unpublished DNR oil and gas records, 1980).

COUNTY	T	R	SEC. #	PERMIT #	FM.	TOTAL DEPTH	STATIC psig PRESSURE/@ DEPTH	OTHER
Antrim	29N	5W	26	29019	Sal.-Niag.	6850	3475/6530	Flowing BHP (psig)
	29N	5W	25	29524			3467/6453	2936
	29N	5W	33	St. Manc. "B" 3-33 31293	Niag.	6810	2122/6636	2145
	29N	5W	34	29668	Niag.		1647/6540	
Benzie	25N	13W	25	Colfax 2-25	Niag.		2858/5698	2834 FBHP
	25N	13W	36	Dinger 1-36	Niag.	6015	2003/5718	1683
Cheboygan	33N	1E	14	USA #1-13A 36269	Niag.	3683	1917/3628	1600 FBHP
	33N	1E	24	32230	Niag.	3772	1905/3668	
	33N	1E	14	St. Forest 2-14	Niag.		1919/3687	
	33N	1E	13	31,922	Niag.	3675		
	33N	1E	14	St. Forest 1-14	Niag.		1951/3678	
	33N	1E	34	33015	Niag.	4444		2194/4161
Crawford	28N	4W	1	31,022	Niag.	6835	3517/6619	3512 FBHP
	28N	4W	2	33,121	Niag.	6858	2526/6707	1695 FBHP
	28N	4W	2	29,247	Niag.	6823	2222/6424	
	28N	4W	2	Wood 4-2	Niag.		1020	
	28N	4W	2	Wood 3-2	Niag.		3497/6834	3013
	28N	4W	4	29605	Niag.	7146	2075/6933	
	28N	4W	4	Kerr 3-4	Niag.		2506/6856	1732
	28N	4W	7	29483	Niag.	7125	3377/6755	
	28N	4W	8	St. Frederic "B" #2-8	Niag.	6790	2449/6790	
	28N	4W	8	St. Frederic "B" #1-8	Niag.		3341/6760	
	28N	4W	10	Kerr 8-10	Niag.		1939/7021	
	28N	4W	10	Kerr 7-10	Niag.	7375	Press. too High	
	28N	4W	10	Kerr 6-10	Niag.	7168	2329/7043	2274
	28N	4W	10	Kerr 5-10	Niag.		2337/7045	2251
	28N	4W	10	Kerr 4-10	Niag.		2450/7034	1677
	28N	4W	10	Kerr 2-10	Niag.	7350	2400/6642	2014
				28852				
	28N	4W	10	Kerr 1-10	Niag.		3665/6685	
				28489				

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III. OCCURRENCE AND DISTRIBUTION OF POTABLE GROUND WATER IN MICHIGAN

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Bedrock Aquifers

AQUIFERS OF THE NORTHERN PENINSULA

Precambrian Aquifers

Precambrian rocks subcrop beneath the glacial drift and crop out in the western and northern Northern Peninsula of Michigan. The oldest exposed Precambrian rocks consist of thick sequences of metasedimentary rocks, including metamorphosed volcano-clastic sediments and lavas, schists and felsic intrusions. Younger Precambrian rocks include the Freda Sandstone, Nonesuch Shale, Portage Lake Lava Series, Copper Harbor Conglomerate, Jacobsville Sandstone, and felsic intrusions. The Freda Sandstone and Nonesuch Shale average 600 feet in thickness where they outcrop and subcrop beneath the glacial drift in northwestern Houghton and Keweenaw Counties and dip about 19° to the northwest. They serve as aquifers for a few wells in Houghton and Keweenaw Counties where they produce from fractures. The Portage Lake Lavas outcrop in central Keweenaw, Houghton, Ontonagon and northern Gogebic Counties. The formation is up to 15,000 feet thick in Keweenaw County and dips from 35° to 60° to the northwest. In Ontonagon County it is generally unfavorable for supplying even small yields, although moderate supplies have been produced in localized areas.

The Jacobsville Sandstone outcrops southeast of the Portage Lake Lavas in the western and northern Northern Peninsula. It ranges from 1000 to 2000 feet in thickness and dips 1° to 5° to the north. Small to moderate yields of water are obtained from fractures in the Jacobsville in Marquette, Baraga, Keweenaw, Houghton, Ontonagon, Alger, Luce and Chippewa Counties. Flowing wells have been reported in the undifferentiated Jacobsville/Munising in Delta, Menominee and Schoolcraft Counties.

Aquifer Characteristics

Precambrian rocks exhibit similar hydraulic properties in that water is produced mainly from fractures and joints in the otherwise relatively impermeable rocks. Fractures generally decrease with depth, and few wells are drilled deeper than 250 feet. Sixty percent of the available well depth values for Precambrian wells are between 50 and 149 feet. The ninety available specific capacity values generally cluster from 0.1 to 0.9 gpm/ft, although a number of values in the 0.01 to 0.09 gpm/ft and 1 to 9 gpm/ft range have been recorded (table 3.1). The 106 available well-capacity values are generally less than 49 gpm (table 3.2). Commonly the metasediments yield 1 to 5 gpm in Marquette County, and small yields are also common in Baraga, Houghton, and Keweenaw Counties. Moderate yields of up to 20 gpm are produced in Ontonagon County and from the Jacobsville Sandstone in the Keweenaw Peninsula.

Water Quality

Water produced from the Cambro-Ordovician system is generally of good quality, but locally contains objectionable amounts of iron. Eighty-seven percent of the 56 reported TDS values are between 100 and 499 mg/l; 79 percent of the 126 specific conductance values are between 200 and 699 umhos/cm (table 3.3). Where the aquifer system is overlain by rocks of the Black River Group, it locally contains hydrogen sulfide gas. In Schoolcraft County elevated levels of sodium and chloride are present and increase toward the south. The chlorides are thought to result from leakage from overlying formations (Sinclair, 1959), and may exceed 1000 mg/l TDS almost to the Straits of Mackinac (pl. 24). Eighty-nine percent of wells for which both water quality and total depth were available are less than 299 feet deep.

Middle Ordovician Aquifer System

The Middle Ordovician Aquifer system includes the Black River and Trenton Groups, which consist of limestone and dolomite with thick interbedded shales and shaly limestone (pl. 24). The units are generally undifferentiated in the subsurface and dip about 40 ft/mile and thicken toward the center of the basin. Near the surface they exhibit solutionally-widened fractures resulting from pre-Pleistocene solution (Vanlier and Deutsch, 1958). Away from the outcrop area, the aquifer system is overlain by the thick Utica Shale of the Richmond Group.

Aquifer Characteristics

Water in the Middle Ordovician aquifer system is produced from solution-widened fractures. The aquifer is used, principally in western Delta and in Menominee County, and in Marquette, Alger and Schoolcraft Counties. Very little information is available for this aquifer system but most of the 18 values for specific capacity range from 0.1 to 9 gpm/ft and well capacity values are generally less than 10 gpm (tables 3.1 and 3.2). The system is under artesian pressure in southern Schoolcraft County, where it is overlain by the Richmond Group. Most of the 27 wells for which hydraulic characteristics and total depth were available were from 10 to 49 feet deep.

Water Quality

The Middle Ordovician aquifer generally provides good quality water and is used extensively where it lies beneath the glacial drift (pl. 24). Seventy-five percent of the 40 reported TDS values range between 200 and 699 mg/l (table 3.3), and most of the 21 specific conductance values were between 200 and 499 umhos/cm. Seventy-four percent of the 46 wells for which water quality and total depths were available were less than 199 feet deep.

Although this aquifer system yields fresh water where it subcrops beneath the drift, it yields saline water in Schoolcraft County where it is overlain by the Richmond Group. Sealing off the overlying Richmond and Cataract Group is recommended practice in well construction to prevent the mixing of saline water with the fresh water from the Trenton-Black River. Locally the water has a high chloride content, and high sulfate levels have been reported in Menominee and Schoolcraft Counties. The system is not a source of fresh water in Mackinac County.

Upper Ordovician-Lower Silurian Aquifer System

In this report the Upper Ordovician-Lower Silurian aquifer system is considered to include the Late Ordovician Richmond Group carbonates of the Stonington and Big Hill Formations, and the Early Silurian Manitoulin Dolomite of the Cataract Group (pl. 24). The aquifer system overlies the Utica Shale, and is overlain by the Cabot Head shaly dolomite. Both consist of shaly dolomite with layers of shale and gypsum. The Upper Ordovician and Lower Silurian are combined because they both contain water of poor quality, but they may or may not be in hydraulic continuity.

The aquifer system dips southeastward, toward the center of the basin at or about 40 ft/mile. At the subcrop the formations exhibit preglacial solutionally-enlarged fractures including bedding plane joints. Fractures are much less evident where shale layers overlie the carbonate rocks.

Aquifer Characteristics

Water from the Upper Ordovician-Lower Silurian aquifer system is produced from fractures and bedding planes enlarged by solution which locally involved the removal of gypsum beds. The aquifer is under artesian pressure where confined by the Cataract Formation. The 10 available values for specific capacity range from 0.1 to 9 gpm/ft and the 6 available well capacity values are less than 49 gpm (tables 3.1 and 3.2). The aquifer system is a water source in Delta and Luce Counties where it crops out and is hydraulically connected with the overlying glacial drift aquifer. It is also used in Schoolcraft County. Well depths for the 5 wells for which both hydraulic characteristics and total depths were available range from 10 to 349 feet (table 3.2).

Water Quality

The water produced from this aquifer system is generally of poor quality and contains large amounts of calcium and sulfate. Where it subcrops beneath the glacial drift, the water is of good quality. Forty percent of the reported TDS values range between 200 and 599 mg/l and 33 percent of the 15 available TDS values exceed 2000 mg/l (table 3.3). It is recommended that sections of the aquifer system that produce saline water be cased off during well construction to avoid contamination of upper or lower aquifers. The aquifer system is generally not used because water of superior quality is often readily available from overlying aquifers. Seventy-two percent of the 25 wells for which water quality information and total depths were available are less than 299 feet deep (table 3.3).

AQUIFERS OF THE NORTHERN AND SOUTHERN PENINSULA

Silurian Aquifer System

Silurian rocks outcrop and subcrop beneath the glacial drift in the southeastern Northern Peninsula and in a small area of the southeastern Southern Peninsula. For the purpose of this report they have been combined into the Silurian aquifer system, a grouping based more on their similar lithologies than hydraulic continuity (pl. 24).

Northern Peninsula

The Silurian aquifer system in the Northern Peninsula includes the Burnt Bluff and Manistique Groups, the Engadine Dolomite, and Salina and Bass Islands Groups. The Burnt Bluff and Manistique Groups and the Engadine Dolomite are important aquifers in their area of outcrop or where they are overlain by glacial drift. They consist of dolomite and dolomitic limestones and range from thinly bedded to massive units. Permeability has been increased by solution, and karst development has occurred in the uppermost calcium-rich units in Schoolcraft and Mackinac Counties (Sinclair, 1959). The formations dip and thicken toward the center of the basin at about 40 ft/mile.

The Salina Group consists of thinly-bedded shale and shaly dolomite with irregular masses of gypsum. Salt beds deposited with the gypsum were subsequently dissolved in of and immediately south of the Straits of Mackinac (Landes, Ehlers, and Stanley, 1945) producing caves into which the overlying rock collapsed. The resulting megabreccia, termed the Mackinac Breccia, is composed of angular blocks of limestone and dolomite with interbedded chert, shale and gypsum remnants from the Salina, St. Ignace and Bois Blanc Formations. The degree of cementation of the blocks varies widely throughout the area, consequently the productivity of the formation varies widely throughout the St. Ignace Peninsula of Mackinac County.

Remnants from the St. Ignace Formation are present in the Mackinac Breccia in southern Mackinac County, on Mackinac Island and on northern Bois Blanc Island. The St. Ignace Formation, consisting of dolomite and shale, may serve as an aquifer where it is present on Bois Blanc and Round Islands, Mackinac County.

Aquifer Characteristics

The Burnt Bluff, Manistique and Engadine are the most widely utilized portions of the Silurian aquifer system. The basal portions of the system are recharged at the Niagaran cuesta in the northeastern Northern Peninsula where water moves downdip along solution-widened bedding plane fractures. Water is also produced from thin, discontinuous but extensive solutionally-developed permeable zones at depth in Mackinac County, and perhaps in Schoolcraft County. Well yields are not in proportion to aquifer thickness, as is the case in sandstone aquifers, but is in proportion to the extent of the permeable zones. The 25 specific

capacity values are evenly distributed in the 0.1 to 0.9, 1 to 9 and 10 to 99 gpm/ft categories (table 3.1). Seventy-nine percent of the 57 well capacity values were below 49 gpm (table 3.2). Eighty-seven percent of the 33 wells for which hydraulic data and total depths were available are between 50 and 199 feet deep. The basal dolomites of the Silurian aquifer system are important water sources in Mackinac County, extreme southeast Delta County and in Schoolcraft County. It may be used in the future in Luce County. Water is under artesian pressure in Schoolcraft County where extensive horizontal beds of confining low permeability materials cause artesian conditions in topographic lows (Vanlier and Deutsch, 1958). Basal portions of the Burnt Bluff are thought to be hydraulically connected to the underlying Cataract Group based upon water-quality analyses from deep wells. The uppermost Silurian rocks in the Northern Peninsula are marginal aquifers, and only produce water from thin localized permeable zones along fractures and crevices in the dolomites or among the poorly cemented blocks in the Mackinac Breccia. There is a wide range of productivity between locations in areas where these formations subcrop and outcrop in Mackinac County.

Water Quality

The shallow zones of the Silurian aquifer system in the Northern Peninsula of Michigan produce good quality water, but deeper zones and zones in contact with gypsum beds locally produce water high in calcium and sulfate. Water produced from the Salina Group and the Mackinac Breccia is generally mineralized from the solution of gypsum. Water produced from depths greater than 250 feet is also often highly mineralized.

Seventy percent of the 35 water samples from the Silurian system in the Northern Peninsula have dissolved solid levels between 100 and 299 mg/l (table 3.3). Fifty-seven percent of the 47 specific conductance levels were between 300 and 599 umhos/cm, but 24 percent exceeded 2000 umhos/cm. Seventy-six percent of wells for which water quality information and total depths were available were less than 199 feet deep (table 3.3). Water samples taken from basal Burnt Bluff Group units have contained high levels of calcium and sulfate, indicating hydraulic connection to the underlying Cataract Group units which characteristically produce water with high levels of calcium and sulfate.

AQUIFERS OF THE SOUTHERN PENINSULA

Silurian rocks of the Bass Islands Group subcrop and outcrop in extreme southeastern Michigan. Water production comes from interconnected fractures and solution cavities, and is used mainly in areas where it underlies the glacial drift. Yields sufficient for domestic purposes are obtained within the subcrop area. Seven of the 12 available specific capacity values range between 1 to 9 gpm/ft (table 3.1). Nine of eighteen well capacity values range between 10 and 49 gpm (table 3.2)

Water Quality

Water produced from the Silurian aquifer system in southeast Michigan is generally of good quality except at depth or where local mineralization has occurred. Little water quality data was available for the Silurian aquifer system because it provides potable water and receives limited use in only a very small section of southeast Michigan (table 3.3). Brines produced from Silurian rocks in the central basin area generally contain dissolved solids to the point of saturation. Fourteen values exceeding 160,000 mg/l TDS have been reported for that area (pl. 24).

Devonian Aquifer System

For the purpose of this report, the units of the Devonian aquifer system have been combined and termed the Devonian aquifer system, a decision based more on their similar lithologic character than to demonstrated hydraulic interconnection (pl. 24). The Bois Blanc Formation, the Detroit River Group, including the Sylvania Sandstone, the Dundee and Rogers City Limestones, and the Traverse Group are included in the aquifer system, which generally consists of dolomite and limestone with interbedded shale, chert and anhydrite stringers. The basal unit of the Detroit River Group is the Sylvania Sandstone, a fine to medium grained sandstone with dolomite which is an aquifer as its area of outcrop in southeast Michigan. The formations dip and thicken toward the center of the basin, where they are productive of oil, gas and mineral brines.

The Devonian carbonates have extensive karst development at their outcrop and subcrop area in the northeastern Southern Peninsula, and have undergone minor solutional activity in the area of the subcrop in the southeastern Southern Peninsula. Extensive fracturing of the Devonian strata has occurred in the northeastern Southern Peninsula (Kimmel, 1973) and is thought to be the result of the removal of underlying Silurian salt beds. Further widening of these fractures has resulted in the formation of numerous sinkholes and other karst features in Alpena and Presque Isle Counties (see Other Geologic Factors, Section 2).

Aquifer Characteristics

Water is produced from Devonian carbonate rocks in the outcrop and subcrop area from solution-widened fractures and crevices along bedding planes. Devonian karst aquifers are important sources of water in the northern Southern Peninsula and are used in Alpena, Presque Isle, Cheboygan, Emmet, Montmorency, Otsego and Charlevoix Counties. They are locally important aquifers in Lenawee, Monroe, Washtenaw and St. Clair Counties where, in the area of subcrop, they provide small industrial and municipal supplies.

The basal member of the Detroit River Group, the Sylvania Sandstone, is an important aquifer in the area of its outcrop in southeastern Michigan. It is a fine to medium grained sandstone, with some dolomite, and yields

up to 50 gpm in southern Wayne County (Twenter, 1975). The 42 specific capacity values for the Devonian aquifer system are predominantly in the range of 0.1 to 9 gpm ft and 80 percent of the 60 well capacity values are less than 49 gpm (tables 3.1 and 3.2). The Devonian aquifer system has flowing wells in Charlevoix, Cheboygan, Emmet and Presque Isle Counties. Sixty-seven percent of the 58 wells for which hydraulic data and total depths were available are between 50 and 149 feet deep (table 3.2).

Water Quality

Devonian carbonate aquifers generally produce good quality water near the surface in the area of outcrop or subcrop beneath the glacial drift where fractured formations have been flushed by fresh water. Mineralization of the ground water increases with depth and is generally higher in areas where an aquifer is overlain by another formation which has restricted the flushing action. Water from the Detroit River Group often contains elevated levels of sulfate from water that has come in contact with interbedded anhydrite stringers.

There is no clear trend to the few total dissolved solids values available for the Devonian aquifer system. Although most samples from the area of subcrop were potable, and had values less than 700 mg/l or less than 1000 umhos/cm (table 3.3). The Devonian aquifer system is heavily mineralized in the central basin where dissolved solids values generally exceed 160,000 mg/l (table 3.3, pl. 24). Bacterial contamination of the aquifer has been a problem due to karst development in Alpena and Presque Isle Counties. There the thin glacial drift is hydraulically connected to the fractured bedrock which transmits pathogens with little attenuation.

Mississippian Aquifer System

The Mississippian aquifer system consists of the Berea Sandstone (in southeastern Michigan), the sandstones of the Coldwater Shale, Marshall Sandstone and Michigan Formation, and the Bayport Limestone (in west-central Southern Peninsula) (pl. 24). The formations dip and thicken toward the center of the basin. Researchers have, at various times, separated the Mississippian sandstones into the Coldwater, Marshall and Michigan Formations, and have more recently grouped them into the Michigan Formation (Moser, 1963). Certainly there is evidence to suggest that hydraulic continuity exists between the sandstones in these three units.

The aquifer system generally consists of sandstone with some shale and siltstone, except for the Bayport Limestone which consists of large erosional remnants of limestone and sandstone. The aquifer system is most productive where it underlies and is in hydraulic continuity with the glacial drift, and decreases in productivity and quality where it is overlain by other bedrock formations. The sandstones are generally productive of fluids throughout the basin, and were formerly sources of mineral brines for a number of commercial salt companies (Cook, 1914). Gas also has been produced from the Michigan Formation "Stray" Sandstone.

The Marshall Sandstone is an important aquifer throughout the southern portion of the Southern Peninsula and is used in Huron, Tuscola, Sanilac, Lapeer, Genesee, Washtenaw, Jackson, Eaton, Calhoun, Barry, Kent and Ottawa Counties. It is also used in Crawford and Roscommon Counties in the northern Southern Peninsula (pl. 24).

The formation consists of locally fractured and generally cemented to locally poorly cemented sandstone with some shale and siltstone. It is highly productive throughout the basin, supplying both drinking water for municipal and domestic systems and commercial brines.

The Bayport Limestone was subject to extensive erosion prior to the deposition of overlying Pennsylvanian rocks, and as a consequence exhibits great variation in thickness throughout its occurrence. It is an important aquifer only where it directly underlies the glacial drift in Kent County, where it has been flushed and recharged by water from the glacial drift. Water is produced from fractured limestone and sandstone.

The Michigan Formation consists of shale with interbedded sandstone, limestone and gypsum. Water is produced from the interbedded sandstones and is often of poor quality. The permeable sandstone beds are of limited areal extent and are difficult to locate, thus reducing the role of this formation as an aquifer in the Mississippian Aquifer System. The Michigan is most productive in Eaton County where it is overlain by, and in hydraulic continuity with, the glacial deposits. Where it is overlain by the Saginaw Formation, it has low permeability and the relatively impermeable shales restrict the upward movement of saline water from the Michigan Formation into the Saginaw Sandstones.

Aquifer Characteristics

The Mississippian Aquifer System is one of the most important and productive aquifers in Michigan. The aquifer system is generally in hydraulic continuity with the drift aquifer in the area where it is overlain by the drift. The aquifer system is further enhanced by naturally induced recharge from surface water bodies, as in Battle Creek (Vanlier, 1966). Forty-one percent of the 112 specific capacity values are from 1 to 9 gpm/ft, with 32 percent from 0.1 to 0.9 gpm/ft and 20 percent from 10 to 99 gpm/ft (table 3.1). Fifty-eight percent of the well capacity values are less than 49 gpm, but values range to 1999 gpm (table 3.2). Flowing wells are reported in Allegan, Barry, Calhoun, Genesee, Hillsdale, Huron, Jackson, Kent, Lapeer, Livingston, Oakland, Ottawa, Sanilac and Washtenaw Counties (Allen, 1974). Sixty-six percent of the wells for which hydraulic data and total depths were available are between 100 and 249 feet deep (table 3.2).

Water Quality

Good quality water is produced throughout the outcrop and subcrop areas of the Mississippian aquifer system, but brines are produced in the central basin area (pl. 24). Saline water production is also reported in west-central Michigan. Sixty-seven percent of the reported 156 TDS values

less than 16,000 mg/l range between 200 and 599 mg/l, and 70 umhos/cm (table 3.3). All 57 TDS analyses available for brine samples from the central basin exceed 16,000 mg/l and generally exceed 160,000 mg/l. Fifty percent of wells for which water quality information and total depths were available range between 100 and 299 feet in depth; and 30 percent range between 700 and 1699 feet in depth.

Pennsylvanian Aquifer System

The Pennsylvanian Aquifer System includes the sandstones of the Saginaw and Grand River Formations (pl. 24). The Pennsylvanian consists of sandstones and shales with interbedded coal and limestone and ranges in thickness from few tens of feet to several hundred feet. The Grand River Formation is extensively eroded and varies in thickness and areal extent. The sandstones of the Grand River Formation are generally hydraulically connected with the underlying sandstones of the Saginaw Formation. Water is produced from the Pennsylvanian aquifer system where it is overlain by, and hydraulically connected with, the drift aquifer.

Aquifer Characteristics

Water production from the sandstones of the Pennsylvanian System is a function of intergranular porosity, which is limited by variations in the cementation, and fractures, which decrease with depth. The thickness of the formation directly controls the yield of the system which generally provides moderate supplies of water where it is relatively thick. The yield is also limited by the opportunity for recharge. Greater yields often occur where the sandstone is overlain by sands and gravels of the glacial drift and where surface water bodies recharge the glacial aquifer, than where it is overlain by shales and clays. The 34 specific capacity values for the Pennsylvanian Aquifer System range from 1 to 99 gpm/ft. Forty-eight percent of the values range from 200 to 299 gpm (table 3.1). Fifty-nine percent of wells for which hydraulic data and total depths were available range between 150 and 299 feet in depth (table 3.2). Water withdrawals in excess of short-term recharge rates have been documented in the Lansing area (Wheeler, 1967, and others).

Water Quality

Water produced from the Pennsylvanian Aquifer System is generally of good quality in the area where the system subcrops beneath the glacial drift and has been flushed (pl. 24). Deep units, however, often yield saline water, even in subcrop areas. Seventy-six percent of the 108 dissolved solids values range between 300 and 699 mg/l, and 84 percent of the 113 specific conductance values range between 400 and 1199 umhos/cm (table 3.3). Fifty-six percent of wells for which water quality data and total depths were available range between 100 and 299 feet in depth. Water quality in Saginaw and Bay Counties is of poorer quality than that of most subcrop areas. This may be the result of upward movement of saline water from the Michigan Formation through poorly plugged wells or naturally occurring fractures in the sandstones.

Aquifers in the Glacial Drift

The Aquifer Characteristics of the Glacial Drift map for Michigan was prepared on the 1:500,000 base of the Surface Formations of the Northern and Southern Peninsulas of Michigan (Martin, 1957). Four major units were defined for the glacial drift aquifer with one additional sub-unit for the Southern Peninsula. These are discussed below. The Northern Peninsula portion of the map is prepared from glacial drift and/or ground-water availability maps in County Progress Reports on ground-water resources, Water Investigation Reports, and a Seafarer Site Survey. The mapped units of the drift as presented in these reports were reinterpreted and assigned to the established aquifer units used for this map.

The Southern Peninsula portion of the map is based on a reinterpretation of the mapped units as presented on Surface Formations of the Southern Peninsula of Michigan (Martin, 1955), Landform Units in northeastern Lower Michigan (Burgis, 1977), and Aquifer Vulnerability to Surface Contamination in Michigan (Dept. of Public Health, 1980). In addition, water well records for the glacial drift in the files of the Michigan Geological Survey were examined to determine the relationship of the drift stratigraphy with the aquifer units used for this map. The analysis of well logs was done for type areas of clearly distinguished surface glacial deposits to determine if a correlation exists. After it was established that a general correlation did exist, approximately 39,300 water and oil and gas well records were examined, with particular attention to those which penetrated the maximum thickness of drift. Well records from all townships on 10 east-west transects and one north-south transect were inspected: 5S, 1N, 5N, 10N, 14N, 20N, 24N, 28N, 32N, and 37N. Several areas were then checked in more detail, they include: Ionia, Clinton, Van Buren, Cass, Sanilac, St. Clair, Alpena, Macomb, Bay, Monroe, Ottawa and Muskegon Counties. This analysis generally validated correlation of mappable glacial units and the aquifer units selected for this map.

GEOLOGY

Southern Peninsula

Unit I: Thin drift (0-30 feet) overlying bedrock.

In the Southern Peninsula sizeable areas of thin drift are restricted to Cheboygan, Presque Isle, Alpena, and Alcona Counties along the northeastern margin of the Peninsula (pls. 15 and 26). Drift in this area is restricted to relatively shallow preglacial and interglacial bedrock channels, filled sinkholes and to solution subsidence features associated with the Mackinac Breccia. On the upland surface drift is present as thin, discontinuous masses, generally less than 10 feet in thickness.

Unit II: Drift is not an aquifer, but may include thin interbedded aquifers at depth.

In general, the drift is not an aquifer in areas where it is composed of glacial lake deposits, or where it is very clayey till. Extensive areas of lake beds exist in the Saginaw lowland and extend across major portions of Midland, Bay, Saginaw, Tuscola, and Arenac Counties. Less extensive areas are present in Gladwin, Isabella, and Gratiot Counties. Lake beds are a dominant feature of the glacial drift in counties marginal to Lake Huron south of Saginaw Bay, the St. Clair River, Lake St. Clair, the Detroit River and Lake Erie including most of Huron, St. Clair, Wayne, Monroe and Macomb Counties. Eastern Sanilac, southeastern Oakland and southeastern Lenawee Counties are also mantled by lake deposits. Till in the moraines that lie within areas of extensive lake beds, such as the Port Huron Moraine in the Saginaw lowland is generally very clay rich, and although it may contain thin sands at depth is generally not an aquifer.

Water is obtained from the lake beds by constructing "jar" wells which are large diameter ceramic tiles sunk below the water table and partially filled with gravel. In some areas, thin beds of outwash within the lake beds are tapped for small to moderate supplies of ground water. The outwash deposits are generally thin and discontinuous with a limited recharge capability. Consequently, such materials are rarely used except for domestic supplies.

Unit IIIA: Drift is generally an unconfined aquifer at or near the surface. At depth the glacial materials may be interbedded aquifers, aquitards and aquicludes.

The glacial drift is an unconfined aquifer at or near the surface in areas of sand dunes, kames, outwash plains, sandy moraines and along major drainage lines. Extensive tracts of sand dunes are present along the Lake Michigan shoreline in western Berrien, Van Buren, Ottawa, and Muskegon Counties. Less extensive tracts exist in Oceana, Mason, Manistee, Benzie, Leelanau, Charlevoix and Emmet Counties. Small areas of sand dunes are present along the eastern shore of Lake Huron in southeastern Alcona and eastern Iosco Counties.

Dunes are composed of very well sorted, permeable sand. Although dunes may be perched above the water table, rapid infiltration rates make these features important for ground-water recharge. Because such features are generally composed dominantly of quartz and feldspar, they do not sorb contaminants effectively and provide little protection for ground water which is extremely vulnerable to pollution from surface and near surface sources.

Extensive areas of ice-contact, water-laid materials (kames) have been identified by Burgis (1977) in the northeastern quadrant of the Southern Peninsula of Michigan. Although very little effort has been made to identify such features elsewhere in the state, it is likely that ex-

tensive areas of kamic topography exist in association with the major morainal belts. Such materials are similar to outwash in composition and aquifer characteristics, and it is likely that most kames have been included with outwash in studies of glacial materials and ground water.

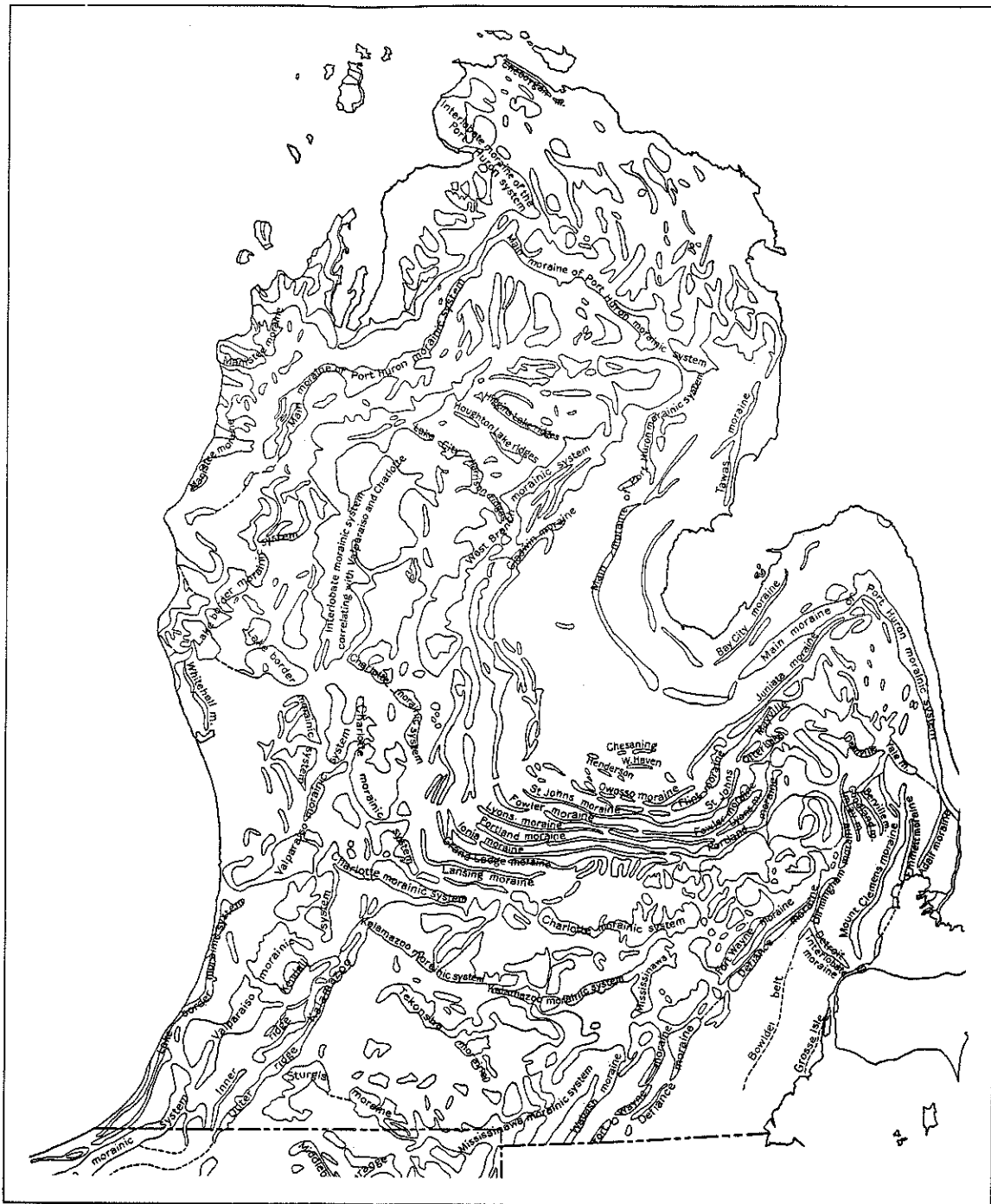
The major morainal tracts of the Southern Peninsula are generally separated by extensive outwash plains and are locally transected by outwash channels. The most extensive aquifers occur under outwash plains. Such features are composed of rather well-sorted sand and gravel that was deposited by streams emanating from melting ice fronts. Locally such features may be overlain by thin lake deposits of till, but in general they are composed of well-sorted, very permeable sediments beneath a thin mantle of relatively permeable soil. Because these water-laid sediments are virtually devoid of fine-grained materials, they do not sorb contaminants effectively and provide little protection for ground water which is extremely vulnerable to surface and near surface contamination, especially contaminants introduced below the soil zone.

Major drainage lines such as those associated with the Ausable, Grand, and Kalamazoo River valleys are underlain by alluvial sediments that generally contain only small amounts of fine-grained material. These deposits generally are excellent aquifers, but provide little protection for ground water. Most small streams flow on relatively limited alluvial deposits, although numerous small streams flow on outwash that has aquifer characteristics very similar to alluvium.

Unit IIIB: Drift may or may not be an aquifer at or near the surface. At depth the glacial materials consist of interbedded aquifers, aquicludes, and aquitards.

The glacial drift is not generally an aquifer at or near the surface in morainal areas and areas of ground moraine. In such areas the surficial glacial materials are generally dominated by poorly sorted ice-contact material, till, that is very slowly permeable, however, at depth interbedded till and outwash deposits typically form complex aquifer systems in such areas. Because the aquifers at depth are generally protected by the overlying ice-contact materials, they are less vulnerable to contamination from surface sources. Such deposits display great vertical and lateral heterogeneity; consequently, it should not be assumed that infiltration and migration routes of ground water will be directly from the surface to materials at depth. Moreover, the anisotropy of such materials may be complicated by the presence of buried erosion surfaces and channels that may direct the flow of water along virtually unpredictable paths.

The pattern of morainal deposits in the Southern Peninsula of Michigan is very complex and was strongly controlled by the distribution of the several lobes of ice that deposited materials across this peninsula (fig. 3.1). With the exception of Monroe County, all counties in the Southern Peninsula of Michigan contain some morainal materials.



The complexity of the glacial deposits in the Southern Peninsula of Michigan is such that morainal areas may contain deposits that lack aquifer characteristics throughout. Moreover, this same complexity also gives rise to localities where the entire column of morainal deposits functions as an aquifer. Such variability may be abrupt with deposits having good aquifer characteristics closely juxtaposed to materials that are aquitards.

Unit IV: Drift may be an unconfined aquifer to bedrock.

Although there are areas of the Southern Peninsula underlain by a single continuous unconfined aquifer to bedrock, very few wells are available which penetrate the drift; hence, this category cannot be delineated for the Southern Peninsula.

Northern Peninsula

The topography in the Northern Peninsula ranges from relatively flat areas of lake and outwash plains to areas of high relief on moraines and bedrock ridges. Relief of the bedrock surface is great, in some places nearly 1000 feet. The topography of flat-lying Paleozoic sedimentary rocks in the eastern part of the Northern Peninsula stands in marked contrast to the irregular resistant ridges, knobs, and valleys developed on the Precambrian rocks of the western part of the peninsula. The dividing line between these distinct physiographic provinces extends from Marquette on the north to the western border of Menominee County on the south.

Variation in bedrock relief has greatly influenced the distribution and thickness of the glacial deposits. In the eastern Northern Peninsula the glacial drift was deposited as a veneer over the flat-lying Paleozoic formations and is relatively uniform in thickness. The drift generally ranges in thickness from zero to 200 feet with thicker, localized deposits including moraines and filled preglacial bedrock valleys. In the western part of the peninsula the glacial deposits show a much wider range in type and thickness. Here the drift ranges from zero on the numerous bedrock ridges and knobs to basin and valley fillage that may be quite thick. Consequently, the glacial aquifer is not present everywhere and bedrock aquifers must be used. In some regions such as Ontonagon County more than 60 percent of the wells are in bedrock (Doonan and Hendrickson, 1969).

Unit I: Thin drift (0-30 feet) overlying bedrock.

Areas of thin drift, ranging from highly permeable beach and dune sand to impermeable lake clay and silt, are widely distributed across the Northern Peninsula (pl. 15). Beach and dune sands are generally related to the postglacial Great Lakes and may stand well above the present levels of Lakes Superior and Michigan as a result of postglacial rebound. Although they may locally yield small to moderate supplies of ground water, these materials are generally above the water table. Such deposits have high infiltration capacities and are

important for recharge of underlying aquifers (Vanlier and Deutsch, 1958). Domestic supplies may be produced from wells in thin permeable drift but, in many areas the thin drift is composed of impermeable lake sediments and wells must be drilled to bedrock or completed as large diameter dug wells in the drift (Doonan and Hendrickson, 1969). The greater surface area of dug wells compensates for the slow percolation rate and permits greater storage capacity.

Unit II: Drift not an aquifer, but may include thin interbedded aquifers at depth.

Some areas of the Northern Peninsula, mostly adjacent to Lake Superior and Lake Michigan, are underlain by glacial lake sediments. The most notable regions are in Mackinac and Delta Counties where Silurian bedrock is close to the surface, and in Marquette, Dickinson, Gogebic, Bataga, and Keweenaw Counties where Precambrian rocks are at or near the surface. Generally, the drift consists of a thin veneer of surface sand underlain by thick clay and silt deposits with interbedded sands (Vanlier, 1963). The water table is usually at or near the surface and locally these sands may provide adequate water for household needs. Basal gravels below lake deposits are also a source of domestic water supply. Most wells in this category in Menominee County tap bedrock aquifers.

According to Vanlier and Deutsch (1958) lake clays, silts, and fine sands exceed 300 feet in thickness in some areas of Chippewa County. A typical section in this area consists of a thick layer of pebble-free red or gray varved clay underlain by layers of finely laminated silt and fine sand. Deposits of this type may locally contain beds of coarse sand or gravel outwash interbedded with the lake sediments. In Chippewa County most of the wells drilled in areas underlain by lake deposits produce water from the outwash or till underlying the lake deposits or from sand and gravel layers within the lake sediments. The interbedded silt and fine sand deposits, called "quicksand" by local drillers, may produce an adequate supply of water from large diameter wells.

Although lake deposits yield little water, they do serve as confining layers for artesian systems and water in the sand and gravel layers may be under sufficient artesian pressure to produce flowing wells. Vanlier and Deutsch (1958) reported that most of the flowing wells in Chippewa County are in areas where the lake clays overlies permeable drift or bedrock.

Unit III: Drift usually unconfined at or near the surface, generally consists of interbedded aquifers, aquicludes and aquitards at depth.

The drift comprising this unit is very diverse in character, ranging from typical end moraine and ground moraine deposits to outwash sediments. The end moraines are widely distributed in the Northern Peninsula and range from unsorted clayey or sandy tills to moraines deposited

in water or moraines later covered by postglacial lakes. The end moraines tend to parallel the Lake Superior shoreline and are well-developed; examples include the Keweenaw Moraine in Baraga County paralleling Keweenaw Bay, and the Munising Moraine in Alger and Luce Counties. Other moraines of prominence are the Marenisco Moraine in the west-central Northern Peninsula and the Newberry Moraine in the east-central Northern Peninsula. The till in the moraines may include sand and gravel outwash. Permeability is low in the clayey till, moderate in sandy or gravelly till, and high in associated sand and gravel outwash. Wells completed in moraines show great variability in yield, ranging from less than 10 gpm to 100 gpm.

This map unit may also include materials previously mapped as swamp deposits and recent alluvium (Doonan and Hendrickson, 1968). These deposits consist of sand, silt, clay, peat, and muck and are present along streams and in topographically low areas. Wells in these areas usually penetrate underlying glacial drift and may yield moderate to large supplies of water. Because of the low population density and few wells, little is known concerning ground water availability of these areas.

Unit IV: Drift may be an unconfined aquifer to bedrock.

Deposits mapped in this category are largely outwash and sandy lake plain deposits greater than 30 feet in thickness and generally directly overlying bedrock. Outwash sediments are deposited by glacial meltwater streams and range in size from sand to gravel. Sorting is usually good and permeability is moderate to high. The largest and most distinctive area of outwash and sandy lake plain occurs in Schoolcraft County and extends eastward into Luce County. Other areas underlain by outwash sediments are widely distributed across the Northern Peninsula, but are generally absent on the Keweenaw Peninsula and in Gogebic and Ontonagon Counties.

The Kingston Plain in Alger and Schoolcraft Counties is an outwash plain formed by meltwater streams when the glacier was stabilized at the position of the Munising Moraine. Other areas of low relief cover about two-thirds of Schoolcraft County and have been previously mapped as "sandy lake plain" (Sinclair, 1959). These deposits contain relatively little silt or clay, although locally some clayey lake deposits are present. Permeability of the outwash and "sandy lake plain" deposits is moderate to high and these areas are potentially good sources of water, however, these areas are sparsely populated and subsurface information is very limited.

In Chippewa County, much of the outwash was deposited in glacial lakes and is deltaic in character. Vanlier and Deutsch (1958) reported that some wells penetrated 145 feet of outwash composed of fine to coarse sand. These deposits yield moderate to large supplies of water.

In Marquette County Doonan and Van Alstine (1979) reported outwash deposits as much as 450 in thickness, however, most wells are less than 50 feet deep. In Iron County, Doonan and Hendrickson (1967) reported that large diameter wells in outwash sediments along streams may yield enough water for municipal or industrial purposes. Most small diameter wells will yield sufficient water for domestic supplies. Specific capacities range from 0.1 to 28 gpm per foot of drawdown.

AQUIFER CHARACTERISTICS

Southern Peninsula

The greatest density of community public water supplies per county is in southeast Michigan, including southeast Oakland, Wayne, Monroe and Macomb Counties (pl. 22). The water supplies in this area are generally served by the Detroit Metropolitan water system which obtains water from Lake Huron and the Detroit River. Bay and Saginaw Counties in east-central Michigan have the second largest density of community public water supplies. They are served by the Bay City and Saginaw-Midland water systems which obtain water from Lake Huron and the Saginaw Bay. A strong correlation exists between the community public water supplies in these areas which depend on surface water and the generally non-productive silt-rich lacustrine deposits which have been classified as Category II aquifers which are generally an aquifer, but may have thin interbedded aquifers at depth (pl. 26). In the Southern Peninsula Category II aquifers had median well capacity value of 37.1 gallons per minute (gpm), and a median specific capacity value of 2.8 gallons per minute per foot of drawdown (tables 3.4 and 3.5).

It should not, however, be assumed that all areas using surface water are underlain by poor aquifers. Lake Michigan is the main water source for most of the west coast municipalities south of Muskegon County including Benton Harbor, St. Joseph, South Haven, Muskegon, and the inland city of Grand Rapids. Most of these municipalities are located in areas of thick glacial drift which is generally an aquifer at the surface or at depth. It is apparent that, in these areas, Lake Michigan provides a more desirable municipal water source although most domestic, industrial and small community water supplies utilize the glacial drift. Grand Rapids, however, is dependent on Lake Michigan because it is located in an area of relatively thin glacial drift (<100 ft.) overlying Mississippian carbonate and sandstone bedrock aquifers which produce poor quality water.

A broad band of relatively thin glacial drift ranging from zero to 100 feet in thickness occurs in the south-central Southern Peninsula from Calhoun and Jackson Counties at the southwest to Sanilac and Arenac Counties at the northeast (pl. 15). Community public water supplies in these counties generally use Mississippian and Pennsylvanian sandstone aquifers, except to the west of the Saginaw Bay where the quality of water in the bedrock aquifers is poor and water is generally obtained from Lake Huron. The glacial drift in this area is generally

TABLE 3.5 - GLACIAL DRIFT SPECIFIC CAPACITY.

Aquifer Category	Specific Capacity (gallons per minute/feet of drawdown)													Total Wells	Median Specific Capacity
	.01-.09	.1-.49	.5-.99	1.01-1.49	1.5-1.99	2.0-4.9	5.0-9.9	10-49	50-99	100-149	150-199	200-300	>300		
	Number of Wells														
Category I															
Northern Peninsula		1	4		1	7	1	5						19	3.5
Southern Peninsula														0	
Category II															
Northern Peninsula	2		5	1		1	3							12	0.9
Southern Peninsula	5	14	14	12	6	15	3	24	12	1	3	1		109	2.8
Category III															
Northern Peninsula	1	9	11	5	3	15	12	11	1					68	3.0
Southern Peninsula	6	14	13	8	2	26	20	75	9	4	1	1	5	184	11.6
Category IV															
Northern Peninsula	1	3	2	1	3	3	3	4						20	2.0
Southern Peninsula														0	

TABLE 3.4 - GLACIAL DRIFT WELL CAPACITY.

Aquifer Category	Well Capacity (gallons per minute)																	Total Wells	Median Well Capacity
	<10	10-39	40-69	70-99	100-149	150-199	200-299	300-399	400-499	500-599	600-699	700-799	800-899	900-999	1000-1099	1100-1199	1200+		
	Number of Wells																		
Category I																			
Northern Peninsula	3	7	2	1	1		1	3	1									19	37.4
Southern Peninsula	1																	1	-
Category II																			
Northern Peninsula	6	9	1															16	13.8
Southern Peninsula	27	56	14	4	5	2	9	4	8	8	6	1	1	1	8		4	157	37.1
Category III																			
Northern Peninsula	25	32	9	2	1		5	3	2			1						80	23.6
Southern Peninsula	44	82	29	14	19	16	41	36	31	39	11	16	12	14	14	5	26	438	236.1
Category IV																			
Northern Peninsula	7	7	1	1	1			1	1						1		1	21	24.5
Southern Peninsula	Insufficient data*																	-	-

*Most wells only partially penetrate glacial drift, thus data is insufficient to delineate this aquifer category in the Southern Peninsula.

TABLE 3.6 - GLACIAL DRIFT WATER QUALITY (TDS and Specific Conductance).

Aquifer Category		TDS (mg/l) and Specific Conductance (micromohos/cm ²)															Total Wells	Median TDS and Specific Conductance
		<100	100-199	200-299	300-399	400-499	500-599	600-699	700-799	800-899	900-999	1000-1099	1200-1299	1300-1399	1400-1499	>1500		
		Number of Wells																
Category I																		
Northern Peninsula	TDS	15	29	6	3	1				1							55	142.5
	Sp. Cond.	8	18	22	13	9	2	2	1					1			66	231
Southern Peninsula	TDS			3													3	250
	Sp. Cond.				1	1	1										3	450
Category II																		
Northern Peninsula	TDS	7	14	5	2	3											33	167
	Sp. Cond.	7	18	24	8	8	3	3	4	4	1						82	166
Southern Peninsula	TDS	2	11	23	27	10	13	6	1		1						94	340
	Sp. Cond.			4	7	20	23	8	10	8		2				4	86	552
Category III																		
Northern Peninsula	TDS	20	41	22	8	1	1	1									94	165
	Sp. Cond.	19	52	47	37	10	4	4	1	2							176	236
Southern Peninsula	TDS	3	38	123	139	74	25	3	4	2	2			1			414	331
	Sp. Cond.		2	18	76	102	85	43	23	7	6	2	3	1	1	3	371	487
Category IV																		
Northern Peninsula	TDS	31	30	10	3				1							1	76	123
	Sp. Cond.	13	41	24	12	3	1	1	2						1		98	187
Southern Peninsula	TDS																	
	Sp. Cond.																	

classified Category IIIB, may or may not be an aquifer at surface, but generally has interbedded aquifers at depth, and the glacial drift is used for small domestic supplies (fig. 3.2). In many areas, however, use of the glacial drift has been less favored because of the larger productivity and better water quality of the bedrock aquifer (pl. 24).

A second inland area of thin glacial drift exists in western Kent and eastern Ottawa Counties, near Grand Rapids. The largest community public water supply in this area, Grand Rapids, obtains water from Lake Michigan and from a local surface water reservoir. Smaller water supplies in the Grand Rapids area obtain water from bedrock aquifers or from the glacial drift which is classified as Category III and generally an aquifer at the surface or has interbedded aquifers at depth.

The largest portion of the Southern Peninsula is classified as Category IIIA and IIIB aquifers which may or may not be aquifers at the surface and generally have interbedded aquifers at depth (pl. 26). Community public water supplies located in this area generally obtain water from the glacial drift, as do most domestic wells. The median well capacity for Southern Peninsula Category III wells is 236.1 gpm, with a median specific capacity of 11.6 gpm per foot of drawdown.

Community public water supplies and domestic wells situated on the Lake Michigan shoreline north of Muskegon County are most often completed in the glacial drift. This is the dominant pattern for the northwestern Southern Peninsula, an area underlain by up to 1400 feet of drift, the thickest accumulations of glacial drift in Michigan (fig. 3.2, pl. 15). Exceptions to this pattern are the community water supplies of Traverse City and Northport which obtain water from Grand Traverse Bay. A number of community water supplies in the northeastern Southern Peninsula are located in a band of thin drift generally less than 50 feet in thickness and often less than 10 feet in thickness occurring from Emmet and Charlevoix, Cheboygan, Montmorency, Presque Isle and Alpena Counties. Water for these systems is obtained from Devonian carbonate bedrock aquifers or from Lake Huron, such as the City of Alpena. The glacial drift in Leelanau, Antrim, Grand Traverse, Cheboygan, Emmet, and Charlevoix Counties includes clay and silt-rich lacustrine deposits classified as Category II aquifers (pl. 26), which generally only have interbedded aquifers at depth. Most domestic supplies in this area, however, utilize glacial drift water sources.

The thin glacial drift in the eastern and southeastern Southern Peninsula does not provide adequate municipal water supplies and are generally classified as Category II aquifers, glacial materials that are fine-grained silts and clays too impermeable to be productive aquifers. The areas of thinnest glacial drift are located in Monroe County, Huron and Sanilac Counties in the "Thumb" area east of Saginaw Bay, and north of Saginaw Bay in Arenac and Iosco Counties. Communities in the coastal areas generally obtain water from the Great Lakes and a large number of the inland communities utilize Mississippian sandstone bedrock aquifers.

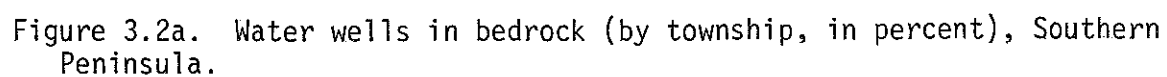




Figure 3.2b. Water wells in bedrock (by township, in percent), Northern Peninsula.

Northern Peninsula

The Northern Peninsula of Michigan has a low population density, even though it has some of the oldest settlements in Michigan, and all but a few of the largest communities are located on the lakeshore. In general community water supplies are obtained from the Great Lakes, regardless of the quality of water in glacial drift aquifers or the bedrock aquifers. The remaining inland communities utilize bedrock aquifers, glacial drift aquifers, or surface water supplies.

A large area of the east-central Northern Peninsula in Schoolcraft, Luce, Alger and Delta Counties is underlain by glacial drift aquifers classified as Category IV, unconfined aquifer to bedrock (pl. 26). There are few settlements in the Schoolcraft-Luce County area, and the few community supplies are generally derived from the glacial drift aquifers. Except for those on the shores of the Great Lakes, settlements in other counties located in this area generally utilize the same glacial drift aquifer. Some domestic wells, however, produce from aquifers which underly the glacial drift. The median well capacity value for Northern Peninsula Category IV aquifers is 24.5 gpm, and the median specific capacity value is 2 gpm/ft (tables 3.4 and 3.5).

A large band of glacial drift trending from Menominee and Dickinson Counties northward to Marquette County is classified as Category III, drift usually unconfined at the surface generally having interbedded aquifers at depth. Due to the generally thin glacial deposits (generally <50 ft., pl. 15), and the good quality of the bedrock aquifers, however, in Menominee, Delta and eastern Dickinson Counties there is widespread use of the Cambro-Ordovician sandstone and Ordovician carbonate aquifers (pl. 24). In contrast, similar glacial deposits located to the west in Iron and Gogebic Counties, an area underlain by Precambrian crystalline and metamorphic bedrock which produces only small flows from fractures, exceed 200 feet in thickness and provide water for the communities of Stambaugh, Iron River and Crystal Falls. Throughout much of Baraga and Houghton Counties, Category III aquifers are the major water source, although some domestic wells produce from the bedrock in this area (pl. 21, pl. 24, fig. 3.2). The median well capacity value of Northern Peninsula wells in Category III aquifers is 23.6 gpm, and the median specific capacity value is 3.0 for 68 values (tables 3.4 and 3.5).

In Chippewa County of the eastern Northern Peninsula, the glacial drift is classified Category II. The glacial drift is composed of lacustrine deposits and is generally not an aquifer. In this area the major municipality, Sault Sainte Marie, obtains water from Lake Superior, and most domestic and small community wells produce from bedrock.

aquifers. Community public water in these areas is often obtained from Lake Superior, while most domestic wells produce from the fractured bedrock rather than glacial drift (fig. 3.2). Although the fine-grained glacial drift of Category II does not generally serve as an aquifer, where it is used it has a median well capacity value of 13.8 gpm/ft for 16 wells.

In areas of thin drift (less than 10 ft.), water production is generally from bedrock wells, and little water production data is available for aquifer Category IV (tables 3.4 and 3.5, fig. 3.2).

Aquifer Vulnerability to Surface Contamination

The Aquifer Vulnerability to Surface Contamination Map (pl. 27), prepared by the Departments of Public Health and Natural Resources, is based on existing hydrogeologic investigations and well records. The areas where aquifer protection is most distinctive coincide with lacustrine plains developed marginal to Lakes Michigan, Huron, and Erie. The most obvious of these areas borders Saginaw Bay and extends southward into Ionia and Eaton Counties. Extending beyond the lacustrine plain to the southwest is an area composed of moraines and till plains which also profices aquifer protection because of the abundance of interbedded clays or clayey till. Other areas of extensive aquifer protection resulting from lacustrine sediments include the area in the eastern portion of the Southern Peninsula to Lake Huron and extending southward to coalesce with the Lake Erie lacustrine plain in southeastern Michigan.

In western Michigan the abundance of clayey sediments occurs in bands close to the Lake Michigan shoreline or somewhat inland. These regions include both areas of lacustrine sediments and areas of the clayey tills in the Lake Border and Valparaiso Morainic systems.

Other areas of aquifer protection in the Southern Peninsula occur along the margins of Grand Traverse Bay extending northward to the Straits of Mackinac and eastward along the Lake Huron shore. These are isolated areas of end moraine and ground moraine complexes and lacustrine plains in which the clayey sediments profice protection for the aquifers.

Extensive areas of aquifer protection occur in the western portion of the Northern Peninsula. These are areas which represent lacustrine plains marginal to Lake Superior, or morainal complexes, and till plains. Ontonagon County has an extensive area of protected aquifers which is largely the result of widespread clayey lacustrine sediments. In contrast, the eastern portion of the peninsula is an area of extensive sandy drift, mostly outwash where areas of aquifer protection are limited to easternmost Chippewa and Mackinac Counties and portions of southeastern Schoolcraft and northwestern Mackinac Counties.

Water Quality

In 1974, the U.S. Geological Survey and the Michigan Geological Survey began a continuing sampling program of carefully selected wells to provide data on the chemical and physical characteristics of natural (uncontaminated) ground waters in Michigan (Cummings, 1980). From 1974 to 1979, 113 samples were studied from wells in 63 counties and analyzed for over 86 parameters including major cation and anions, trace metals, pesticides and others. Seventy-seven samples were from the glacial drift; 36 were from bedrock. The average depth of the drift wells was 95 feet; the average depth of the bedrock wells was 225 feet.

Ground water quality was found to vary considerably within the state (table 3.7). Total dissolved solids, for example, ranged from 20 to 2000 mg/l, hardness (as CaCO_3) from 9 to 900 mg/l, and iron from .01 to 29 mg/l. With the exception of iron (maximum 29 mg/l), aluminum (maximum 44 mg/l), and titanium (maximum 3.6 mg/l), most substances were within the range common for ground waters. Low dissolved solids generally were indicative of calcium carbonate waters and higher dissolved solids generally reflected increases in sodium, sulfate and chloride. Concentrations of trace substances appeared unrelated to dissolved solids.

As would be expected, dissolved solids tended to be highest in samples from bedrock wells. The average TDS of samples from glacial drift wells was 241 mg/l compared with 535 mg/l for samples from bedrock wells (table 3.8, figs. 3.3 to 3.6). Mineralization of water tended to increase with depth and, in drift wells, was found to be highest in outwash. Higher barium and ammonia concentrations were found in the southeastern portion of the Southern Peninsula. Iron concentrations were highest in the southeastern Southern Peninsula and the Northern Peninsula. Lead concentrations were highest in the north-central Southern Peninsula. Fifty percent of the samples were classified as very hard (equal to or greater than 190 mg/l).

Concentrations were compared with U.S. E.P.A. Drinking Water Standards. Lead exceeded the primary MCL in 13 percent of the samples and iron and manganese in over 40 percent of the samples. Few samples of other parameters exceeded primary or secondary MCL's (table 3.9).

Data obtained in the 1979-81 E.P.A.-U.I.C. study indicate that the quality of water from the glacial drift in Michigan is generally good, although, as in the U.S.G.S. study, high concentrations of calcium and magnesium were found to lead to increased hardness and ground water was found locally to contain objectionable amounts of iron. The level of dissolved solids in ground water from the drift in the Northern Peninsula (pl. 25, table 3.6) is generally lower than the Southern Peninsula due probably to the differences in bedrock and hence the mineralogical composition of the drift. Of 515 total dissolved solids values collected from the drift aquifer in the Southern Peninsula,